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STABILITY AND CONTROL CHARACTERISTICS OF THE M2-F2 LIFTING BODY MEASURED DURING 16 GLIDE FLIGHTS

By Euclid C. Holleman

Flight Research Center
Edwards, Calif.

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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STABILITY AND CONTROL CHARACTERISTICS OF THE M2-F2 LIFTING BODY MEASURED DURING 16 GLIDE FLIGHTS*

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SUMMARY

Sixteen glide flights with the M2-F2 lifting-body research vehicle were analyzed to obtain a measure of some of the static and dynamic stability and control and handling characteristics for a Mach number range of 0.4 to 0.7. The vehicle was statically and dynamically stable in the regions in which it was predicted to be stable. The upper flap was about twice as effective as the lower flap as a pitch control. The flight stability and control results agreed reasonably well with the wind-tunnel predicted characteristics.

The M2-F2 handling qualities with dampers on and rudder-to-aileron interconnect operative were rated satisfactory for the M2-F2 research mission by the four pilots in the program. The predicted unacceptable handling characteristics of the basic vehicle were observed in flight. Various handling-qualities criteria predicted handling that was in general agreement with the actual pilot evaluation for the M2-F2 vehicle. The vehicle has the lift capability and maneuverability for satisfactory approach and landing as a glider at a selected landing site. The approach and landing piloting task was demanding and required detailed preparation and practice for the flight and complete concentration during the maneuver.

INTRODUCTION

For several years, the National Aeronautics and Space Administration has been studying the feasibility of using lifting configurations for entry (refs. 1 to 4, for example). This research has resulted in configurations that can be maneuvered during entry, which provides the operational flexibility desired for manned operations and perhaps for horizontal landing. The NASA Flight Research Center, at Edwards, Calif., is conducting a flight program to investigate the feasibility of controlling, maneuvering, and landing these configurations. Included in the program is the correlation of stability, control, lift, drag, and aerodynamic load characteristics of these vehicles with predictions based on wind-tunnel tests and other methods. The results of a flight investigation with a lightweight (1182 lb (536 kg)) lifting body, reported in references 5 and 6, verified the feasibility of piloting a lifting-body vehicle and landing it horizontally.

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To extend the lightweight lifting-body results to a more nearly operational weight and to higher speeds, the stability, control, lift, drag, handling qualities, and landing characteristics of heavier (6000 lb (2722 kg)) vehicles are being investigated. The objectives of this program, which are similar to those of the lightweight lifting-body program, are to investigate the requirements for piloted flight with normal landing at a selected site. The planned program will include flight investigations of the handling qualities and landing characteristics of the NASA M2-F2 and HL-10 and U. S. Air Force SV-5 lifting bodies. The program is being conducted jointly by the NASA Flight Research Center and the Air Force Flight Test Center.

The stability and control results from 16 unpowered flights of the M2-F2 vehicle are presented in this paper and are compared with wind-tunnel and simulator tests and with handling-qualities criteria. The lift and drag results are reported in reference 7.

SYMBOLS

Measurements for this investigation were taken in the U. S. Customary System of Units. Equivalent values are indicated in the International System of Units (SI) in the interest of promoting the use of this system in future NASA reports. Details concerning the use of SI, together with physical constants and conversions, are given in reference 8.

For comparison with full-scale wind-tunnel data, the aerodynamic coefficients presented are based on reference areas and lengths (see table I). The sign convention used is shown in figure 1.

a_z — normal acceleration of vehicle at center of gravity, g units

b — reference body span, feet (meters)

C_L — lift coefficient, $\frac{\text{Lift}}{\bar{q}S}$

C_{L_α} — lift-curve slope, $\frac{\partial C_L}{\partial \alpha}$

C_l — rolling-moment coefficient, $\frac{\text{Rolling moment}}{\bar{q}Sb}$

C_{l_β} — change in rolling-moment coefficient due to sideslip, $\frac{\partial C_l}{\partial \beta}$

$C_{l_{\delta_a}}$ — change in rolling-moment coefficient due to aileron deflection, $\frac{\partial C_l}{\partial \delta_a}$

C_m — pitching-moment coefficient, $\frac{\text{Pitching moment}}{\bar{q}Sc}$

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C_{m_q} change in pitching-moment coefficient due to pitching, $\frac{\partial C_m}{\partial \frac{qc}{2V}}$

C_{m_α} static longitudinal stability, $\frac{\partial C_m}{\partial \alpha}$

$C_{m_{\dot{\alpha}}}$ change in pitching-moment coefficient due to rate of change of angle of attack, $\frac{\partial C_m}{\partial \frac{\dot{\alpha} c}{2V}}$

$C_{m_{\delta_l}}$ longitudinal control-effectiveness derivative, $\frac{\partial C_m}{\partial \delta_l}$

C_N normal-force coefficient, $\frac{\text{Normal force}}{\bar{q}S}$

c reference longitudinal length, feet (meters)

F_{st} longitudinal stick force, pounds (newtons)

g acceleration due to gravity, 32.2 feet/second^2 (9.8 meters/second^2)

h altitude, feet (meters)

I_X rolling moment of inertia (body axis), slug-foot^2 (kilogram-meter^2)

I_{XZ} product of inertia referred to the body X and Z axes, slug-foot^2 (kilogram-meter^2)

I_Y pitching moment of inertia (body axis), slug-foot^2 (kilogram-meter^2)

I_Z yawing moment of inertia (body axis), slug-foot^2 (kilogram-meter^2)

K_I rudder-to-aileron interconnect ratio, $\frac{\delta_r}{\delta_a}$, degree/degree

K_p roll-damper gain, $\frac{\delta_a}{p}$, degree/degree/second

K_q pitch-damper gain, $\frac{\delta_l}{q}$, degree/degree/second

K_r yaw-damper gain, $\frac{\delta_r}{r}$, degree/degree/second

$L_\beta = \frac{C_{l_\beta}\bar{q}Sb}{I_X}$, $\frac{1}{\text{second}^2}$

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$L_{\delta_a} = \frac{C_{l\delta_a}\bar{q}Sb}{I_X}$, $\frac{1}{\text{second}^2}$

M Mach number

$M_{\delta_l} = \frac{C_{m\delta_l}\bar{q}Sc}{I_Y}$, $\frac{1}{\text{second}^2}$

m mass, slugs (kilograms)

P period of underdamped oscillation, seconds

p_{ss} steady-state rolling velocity, degrees/second

p rolling velocity, degrees/second

q pitching velocity, degrees/second

$\bar{q}$ dynamic pressure, pounds/foot^2 (newtons/meter^2)

r yawing velocity, degrees/second

S reference planform area, feet^2 (meters^2)

$T_{1/2}$ time required for transient oscillation to damp to one-half amplitude, seconds

t time, seconds

V true velocity, feet/second (meters/second)

V_i indicated airspeed, knots (meters/second)

W vehicle weight, pounds (kilograms)

α angle of attack, degrees

$\dot{\alpha}$ rate of change of angle of attack with time, per second

β angle of sideslip, degrees

δ_a total aileron deflection, degrees

δ_l lower pitch-flap deflection, degrees

δ_r total rudder deflection from flare, degrees

δ_{r_o} rudder flare angle (each rudder flared outward), degrees

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δ_{st} — longitudinal control-stick deflection, inches (centimeters)

δ_u — average upper-pitch-flap deflection, degrees

ζ — damping ratio of longitudinal oscillation

ζ_d — damping ratio of Dutch roll oscillation

θ — pitch angle, degrees

ρ — air density, slugs/foot^3 (kilograms/meter^3)

τ_R — roll-mode time constant, seconds

φ — bank angle, degrees

ω_d — undamped Dutch roll natural frequency, radians/second

ω_n — undamped longitudinal natural frequency, radians/second

ω_φ — undamped natural frequency of numerator quartic in the roll-to-aileron-input transfer function, radians/second

Subscript:

max — maximum

DESCRIPTION OF THE VEHICLE

The M2-F2 vehicle (figs. 2(a) to 2(d)) is a single-place lifting-body vehicle with conventional fighter-aircraft-type cockpit arrangement and cockpit controls. The basic shape of the vehicle is a blunt 13° half cone with tapered afterbody and with two vertical fins and rudders. The vehicle is similar to, but heavier than, the M2-F1 vehicle previously flight tested and reported on in references 5 and 6. The M2-F2 vehicle afterbody was extended to provide a smaller base area, and the landing gear is extensible. The location of the pilot is more forward on the body than in the M2-F1, and the M2-F1 aileron controls outboard of the vertical surfaces were eliminated. Pertinent dimensions are given in table I and figure 1.

Aerodynamic control was provided by upper and lower flaps and rudders. The rudders deflected outward from a rudder-flare setting of 5°. The upper flaps provided aerodynamic longitudinal trim and, with a rudder-to-aileron interconnect, roll control. The lower flap gave pitch-attitude control and longitudinal trim. The upper and lower flaps were positioned to insure longitudinal stability at the desired flight condition.

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The aerodynamic control surfaces were actuated by hydraulic systems that accepted commands from both the pilot and the stability augmentation system. Stick and pedal-force feel were provided the pilot by coil-spring bungees which gave force proportional to stick or pedal movement.

Simple stability-augmentation systems provided damping augmentation in all three axes. The pitch damper actuated the lower flap, and roll damping was obtained by differentially deflecting the upper flaps. Nominal damper gains were 0.6 in pitch, 0.4 in roll, and 0.6 in yaw; however, the damper gains could be adjusted in flight by the pilot. An interconnect of rudder deflection proportional to aileron deflection was provided to decrease the adverse yaw due to aileron deflection. The interconnect ratio was nominally set at -0.5; however, the ratio could also be adjusted by the pilot.

Basic instrument displays of airspeed, altitude, angle of attack, normal acceleration, control-surface positions, turn rate, and lateral acceleration were provided for the pilot. A nose window gave approximately 10° of downward vision below the instrument panel and about ±20° of side-to-side vision to insure adequate outside visual reference for approach and landing.

INSTRUMENTATION

All flight data were recorded by using standard sensors, a pulse code modulation data-acquisition system, and a telemetry transmission and decommutator for standard digital recording tape. Sampling rates of 200 per second were available for all the quantities of interest: aerodynamic control positions; pilot's stick position; rudder-pedal position; altitude; airspeed; stability-augmentation-system actuator positions and gain-switch positions; angle of attack; angle of sideslip; roll, pitch, and yaw velocity; pitch and roll angle; and normal, lateral, and longitudinal acceleration. The accuracies of these recorded quantities are believed to be within 2 percent of the full-scale recording range for the data-recording system.

Table II shows the range of recorded quantities pertinent to this report. Estimated maximum errors (ref. 7) in vehicle weight were ±20 pounds (±9 kilograms); in dynamic pressure, ±2.65 pounds/foot^2 (±126.9 newtons/meter^2); and in Mach number, ±0.01. The existence of other errors in the recorded data was recognized, and an analysis of the effects of actual instrument installation angles and locations was made. The maximum errors were 4 percent in pitch rate, 2 percent in roll rate, and 2.5 percent in yaw rate. The maximum errors in recorded acceleration at the vehicle center of gravity due to accelerometer location off the nominal center-of-gravity location were 3.5 percent in lateral acceleration and 1 percent in normal acceleration. The errors in these quantities were expected to be less than the maximum error during nominal maneuvering, so no corrections were made to the experimental data.

During the wind-tunnel tests with the flight vehicle in the Ames Research Center's full-scale wind tunnel, the angle-of-attack vane was calibrated over a range of angle of attack of -10° to 30° at a Mach number of 0.25. A least-squares analysis (ref. 7) of the calibration data indicated approximately ±0.7° standard error of estimate (68 percent of the data scatter within the error band).

Longitudinal stick forces were estimated from the recorded stick-position data by applying the known force-feel spring constant.

FLIGHT TESTS

Test Methods

After launch from a B-52 airplane at about 45,000 feet (13,716 meters) altitude and a Mach number of about 0.6, standard flight test maneuvers were made during gliding descent to assess the stability, control, and handling characteristics of the M2-F2 vehicle. Turns and pullup maneuvers provided variations of control and response parameters with lift, and control pulses were made at specified flight conditions for vehicle response determination. Flares at altitude and for landing provided some data variations with angle of attack. Gliding flight without angular accelerations yielded control trim information.

Pilot ratings of the handling qualities of the vehicle based on a modified Cooper (ref. 9) rating scale (table III) were obtained immediately after flight. The pilots were thoroughly familiar with the desired flight plan and predicted handling qualities of the M2-F2 as a result of practice on the complete six-degree-of-freedom simulator with a fixed-base cockpit similar to that of the actual flight vehicle.

Flight Envelope

A typical flight time history is presented in figure 3, and the flight envelope covered during the glide program is shown in figure 4. Indicated airspeeds ranged from about 165 knots (85 meters/second) at launch to 310 knots (159 meters/second) prior to the flare to landing. Landing touchdowns were made at velocities as low as 155 knots (80 meters/second). Maximum Mach number was about 0.70, and maximum dynamic pressure was approximately 310 pounds/foot^2 (14,840 newtons/meter^2). Angles of attack from 16° to -5° were flown, and normal accelerations as high as 2g were reached. Turn maneuvers were made with 60° or less bank angle; however, bank angles of at least 100° were encountered during unplanned oscillation maneuvers.

RESULTS AND DISCUSSION

The results of 16 flight tests of the M2-F2 vehicle are presented in terms of longitudinal trim, static stability, flap effectiveness, and general handling in normal gliding flight and during approach and landing. Vehicle response and handling-qualities data were also obtained with the stability augmentation system off and with a range of rudder-to-aileron interconnect ratios. The flight results are compared with full-scale wind-tunnel measured trim and other characteristics derived from the wind-tunnel tests. Comparisons of pilot evaluation of vehicle handling are also made with some proposed entry vehicle and airplane handling-qualities criteria.

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Static Longitudinal Stability and Control

Trim characteristics. – The longitudinal control required to trim the M2-F2 vehicle over a Mach number range of 0.4 to 0.7 is summarized as a function of angle of attack in figure 5(a) for two upper-flap positions. Data are for a center-of-gravity position of 54 percent of the reference length with the gear up and rudders flared 5.0°. The δ_l variation with angle of attack agrees well with the results of the flight-vehicle wind-tunnel tests (ref. 10) for a rudder flare of 0°. Insufficient wind-tunnel data were available for a comparison over the range of the flight tests at the desired rudder-flare position; however, it was indicated that 2° to 3° of M2-F2 nose-down lower-flap deflection would be required to trim the 5° of rudder-flare pitching moment.

The installation of the XLR-11 rocket engine (fig. 2(d)) in the M2-F2 required a cutout and fairing of the lower pitch control flap. Two flights were made with this configuration, and some longitudinal trim data were obtained. The center of gravity of the vehicle was maintained at 54-percent reference length for the tests. Figure 5(b) shows the lower-flap deflection required for trim for two positions of the upper flap, -12.4° and -14.8°. A linear variation of angle of attack for a variation of δ_l was noted, and the effectiveness of the modified lower flap (an incremental change in α for an incremental change in δ_l) appeared to be the same as before the engine installation. Some 5° or 6° less lower flap were required for trim at a given angle of attack with a similar upper-flap setting. Small-scale wind-tunnel tests (unpublished) did predict the expected pitching-moment change due to the fairing, although slight model differences precluded actual trim comparisons.

Figure 6 indicates the trim effectiveness of the upper flap for a lower-flap deflection of 17° and a Mach number range of 0.42 to 0.59 for the basic M2-F2 configuration (before engine installation). A comparison with the upper-flap effectiveness predicted by the full-scale wind-tunnel tests shows fair agreement.

Stability variation with lift. – Variations of effective static stability and control were obtained during pullups and descending turns. Figure 7 presents a time history of a typical turn initiated at about 16,000 feet (4877 meters) at a Mach number of 0.48 and terminated at 10,000 feet (3048 meters). The dynamic pressure increased from about 190 pounds/foot^2 to 240 pounds/foot^2 (9100 newtons/meter^2 to 11,496 newtons/meter^2) during the turn. The upper flap was set at -11.2°. Pitch, roll, yaw, and interconnect gains were 0.6, 0.4, 0.6, and -0.5, respectively. The pilot rated the longitudinal stability and control of the augmented vehicle during the maneuver as 2.

The variations of several longitudinal parameters with control stick and surface are presented in the cross plots of figure 8. The effect of dynamic-pressure variation during the maneuver is evident in the loop in the normal acceleration. When dynamic pressure was accounted for, either by calculation as with C_N or by the variables being equally dependent on dynamic pressure as with α and δ_l, the effect was not apparent.

Since in all the flights reported herein the vehicle was operated as a glider, none of the maneuvers were performed at constant flight conditions. Nevertheless, the variations show stable, near-linear response with the lift parameters.

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Pullups following launch and during flares also provided apparent stability information. Typical results obtained immediately after launch are shown in figure 9. Mach numbers ranged from 0.64 to 0.70, and the vehicle's altitude decreased from 43,000 feet to 35,000 feet (13,106 meters to 10,668 meters). Dynamic pressure increased from 95 pounds/foot^2 to 146 pounds/foot^2 (4550 newtons/meter^2 to 6993 newtons/meter^2). Nearly linear variations with pilot control are shown.

Longitudinal stick-force variations during the maneuvers are also presented in figures 8 and 9 to give an indication of the stick forces required to maneuver the vehicle. These data were derived from the stick-deflection data by applying the feel spring constant of 5 pounds per inch (8.75 newtons per centimeter) of stick travel. A stick force per g of about 15 pounds to 18 pounds (67 newtons to 80 newtons) was indicated.

The apparent stability, angle-of-attack response to longitudinal control, and stick-force gradient for the flight Mach number range of 0.4 to 0.7 are presented in figure 10. Maneuvers with large variations (greater than 10 percent) in dynamic pressure were not used in the stick force per acceleration data, and average dynamic pressures were used to present the data on a common base for comparison. These parameters also appear to be almost invariant with Mach number over the range presented, and reasonable agreement with the data of reference 10 is shown for these flight-measured parameters.

The stick force per g levels for the flight conditions tested were typical of maneuverable airplanes, ranging from about 25 pounds per g (111 newtons per g) to about 8 pounds per g (35.5 newtons per g) as dynamic pressure increased. Maneuvering during actual entry is expected to be at lower dynamic pressures, which would result in higher stick-force gradients; however, little maneuvering is expected to be required in this flight region. The longitudinal-maneuvering stability and control were rated by the pilots as completely satisfactory with the pitch damper operating (pilot rating of 2 to 3).

Upper-flap effectiveness. – To determine the maneuvering effectiveness of the upper flap as a longitudinal control, a push-over and pullup was made (fig. 11) at an altitude of about 25,000 feet (7620 meters) and a Mach number of about 0.45. The dampers-off portion of the record exhibits low damping; however, upper-flap control provided adequate vehicle rotation for maneuvering (fig. 12). Angle of attack per unit upper-flap deflection was some 60 percent higher than for the lower flap, resulting in an apparent stability of about one-half that with the lower-flap control, when considering either angle of attack or lift response as a result of longitudinal control. Comparison with the predicted maneuvering effectiveness (ref. 10) of the upper flap shows reasonable agreement with the full-scale wind-tunnel tests of the M2-F2 vehicle without rudder flare. It was indicated that about 1° of nose-down upper flap was required to trim for the rudder flare.

Apparent stability during landing. – Although the M2-F2 vehicle was statically stable longitudinally, as shown by the flare at an altitude of 20,000 feet (6096 meters) in figure 13, an apparent instability existed during the flare to land. This instability is illustrated in figure 14, which shows the stick deflection and lower-flap control used during landing as a function of angle of attack. A stable variation of control (decreasing deflection with increasing angle of attack) existed from flare initiation at a height above the ground of 1200 feet (366 meters) to gear deployment at about 20 feet (6.1 meters) above the ground. An apparent neutral stability was evident just prior to gear deployment. At gear deployment, a trim change requiring about 5° of lower-flap deflection is indicated, and a trim change of this magnitude was predicted by the full-scale wind-tunnel tests (ref. 10). With the gear down in proximity to the ground (within a body length), the vehicle was apparently statically unstable, possibly because of ground effects. The pilots did not object to this instability, inasmuch as only a few seconds (actual time ranged from 1.4 seconds to 8 seconds) elapsed between gear deployment and landing touchdown and the vehicle was being closely controlled during this time.

Dynamic Longitudinal Stability

The dynamic stability of the vehicle was investigated by making rapid control inputs during stabilized flight with pitch stability augmentation off and the roll, yaw, and rudder-to-aileron interconnect operational and allowing the free oscillation to subside with controls fixed. Figure 15 illustrates the dynamic longitudinal response characteristics of the M2-F2 vehicle at $M = 0.62$ and $h = 37{,}000$ feet (11,278 meters). The longitudinal response was stable with a damping ratio of 0.1 to 0.2. The addition of damping augmentation gave near-critical damping and provided satisfactory dynamic longitudinal-stability characteristics.

The flight-measured longitudinal characteristic period and damping are presented in figures 16(a) and 16(b) as functions of angle of attack and Mach number for a center-of-gravity position of 54 percent $\bar{c}$. The measured natural period and damping were modified by the test-environment parameters, inasmuch as the test maneuvers could not be obtained at the desired constant test conditions. No effects of the angle-of-attack and Mach number variables on the experimental data were apparent in the limited test data obtained. The static stability, lift, and drag of the M2-F2 were measured during wind-tunnel tests at $M = 0.25$ utilizing the flight vehicle (ref. 10) and at 0.6 utilizing a 1/12-scale model (unpublished data). Using the wind-tunnel derivatives, the period and damping parameters were computed for comparison with the flight data by utilizing the following approximate expressions:

$$P\sqrt{\bar{q}} = 2\pi\sqrt{\frac{I_Y}{S\bar{c}C_{m_\alpha}}}$$

$$\frac{1}{\rho V T_{1/2}} = 0.36\left[\frac{S}{m}C_{L_\alpha} - \frac{S\bar{c}^2}{2I_Y}\left(C_{m_q} + C_{m_{\dot{\alpha}}}\right)\right]$$

The flight test values of the period and time-to-damp parameters are somewhat lower than predicted from the wind-tunnel-measured characteristics, indicating higher longitudinal stability and damping than predicted. The short-period variation computed from the lower Mach number tests with the flight vehicle is in better agreement with the experimental data than are the results from the scaled model at a higher Mach number. The experimentally measured damping, however, being a function of velocity, is in better agreement with the $M = 0.6$ wind-tunnel data.

Dynamic Lateral-Directional Stability

Dampers-off rudder pulses were also recorded to assess the lateral-directional stability characteristics of the vehicle over a Mach number range of 0.53 to 0.61. An example time history of the vehicle response to a rudder pulse is shown in figure 17. Roll response to the rudder through the dihedral effect was high. The roll-to-yaw ratio appears to be about 4. Although the response was stable and damped, the damping was light, with a damping ratio of less than 0.1.

Only limited lateral-directional response data were obtained in flight with the roll and yaw dampers inoperative. The Mach number and altitude ranges covered were 0.53 to 0.61 and 23,000 feet to 38,000 feet (7010 meters to 11,582 meters), respectively. The period and damping parameters are presented in figure 18 and show some variation, decreasing with increasing angle of attack, for the limited range of the tests. The results are compared with the period and damping characteristics computed from wind-tunnel static derivative measurements and from estimated damping derivatives.

Lateral-directional stability derivatives were measured for the flight vehicle at $M = 0.25$ (ref. 10) and for the 1/12-scale model at $M = 0.6$ (unpublished). Utilizing the derivatives and a three-degree-of-lateral-directional-freedom computer program, the period and damping characteristics of the M2-F2 were computed for $M = 0.25$ and 0.6.

The flight-measured period characteristics substantiated the predictions based on the wind-tunnel data. The estimated damping characteristics showed longer times to damp, i.e., poorer damping, than measured in flight. The slight variation with angle of attack was indicated.

Lateral Controllability

Calculated. – The controllability of the basic M2-F2 at subsonic speed was predicted to be poor by studies utilizing the U.S. Air Force complete six-degree-of-freedom M2-F2 flight simulator. Many of the classical problems of stability and control, such as control reversal, pilot- or system-induced oscillations, low damping, dynamic instability, and pitch up, occurred in some part of the flight envelope. Also, the ailerons and rudders commanded significant response in the undesired control modes. The predicted response of the basic M2-F2 to 5° of aileron is shown in figure 19(a) for a Mach number of 0.4 and a dynamic pressure of 150 pounds/foot^2 (7182 newtons/meter^2). Note that the overall response to a step aileron deflection was opposite to the control deflection and that the lateral-directional response was lightly damped. Initial roll was in the commanded direction, but the adverse yaw and dihedral effect caused the roll to reverse. Figure 19(b) shows the predicted response of the vehicle to a step rudder deflection (-2.5°). Initial roll was negative, but as sideslip developed, roll was positive. Roll response to -2.5° of rudder through the dihedral effect was greater than the response to 5° of aileron deflection.

For the ailerons to be effective in producing roll rate, sideslip must be controlled to small values, which suggests a rudder deflection proportional to aileron-deflection interconnect. Figure 20 summarizes the M2-F2 roll-response characteristics as a function of interconnect ratio for M = 0.4. The unaugmented steady-state M2-F2 roll-rate response to aileron provides the base for the basic M2-F2 roll-rate response with various rudder-to-aileron interconnect ratios. The range of angle of attack considered was 0° to 12°. Note that an interconnect ratio of about -0.25 to -0.3 was required for roll in the commanded direction and that roll rate was augmented by the rudder deflection at the higher interconnect ratios.

In addition to the requirement for an interconnect, it was apparent that additional damping was necessary to obtain satisfactory handling qualities. The predicted response to separate aileron and rudder steps with nominal interconnect and damping augmentation gains is shown in figures 21(a) and 21(b). The response to both aileron and rudder was in the correct direction and was well damped. Rudder, through dihedral effect, gave higher roll rates than the ailerons, however.

The aileron roll reversal illustrated for $\alpha = 0°$ and M = 0.4 for the unaugmented vehicle (fig. 19(a)) occurred over much of the subsonic flight envelope. The predicted lateral handling characteristics of the M2-F2 at low subsonic speeds without damping augmentation are summarized as a function of interconnect ratio and angle of attack in figure 22. The roll response to aileron was predicted to be sluggish at interconnect ratios of less magnitude than about 0.3 at low angles of attack and at higher interconnect ratios at higher angles of attack. However, the use of higher interconnect ratios at negative or low positive angles of attack can result in induced lateral-directional oscillations. With light damping of the basic configuration, pilot-induced and sustained oscillations were possible with nigh interconnect ratios. With some combinations of damper-systems gains, sustained lateral-directional oscillations were also predicted by the M2-F2 simulator. These characteristics existed to some extent over the entire low Mach number range so that different interconnect ratios were required for different flight angles of attack and Mach numbers.

<u>Flight verification</u>. – Only a part of the M2-F2 flight envelope was covered during the flight program. Angles of attack from -5° to 16° were reached. Much of the flight experience was with an interconnect ratio of -0.5. For research purposes, the interconnect ratio was varied from 0 to -1.0 and inadvertently to -1.4. In-flight pilot evaluation and ratings, in general, confirm the predicted controllability of the vehicle. Roll reversal was encountered at low interconnect ratios. With dampers on, the vehicle was controllable with reversed aileron control inputs and was rated at 8.

Time histories of roll maneuvering at three interconnect ratios (-0.20, -0.53, and -0.79) with normal damper gains ($K_q = 0.6$, $K_p = 0.4$, $K_r = 0.6$) and h = 39,000 feet (11,887 meters) are shown in figure 23. The angle of attack was 7°. Roll reversal was apparent for $K_I = -0.20$ (fig. 23(a)) as negative aileron control was maintained and roll was initially left as commanded but then reversed to right roll. At an interconnect ratio of -0.53 (fig. 23(b)), roll rate more nearly followed aileron control. Increased roll in the desired direction was evident (fig. 23(c)) at a higher interconnect ratio (-0.79), giving indications that induced roll by the rudder through dihedral effect provided roll rates greater than with $K_I = -0.53$.

During a maneuver to obtain stability derivatives with $K_I = -0.49$, the M2-F2 vehicle was stabilized at about -2° angle of attack and the roll- and yaw-damper gains were turned to zero. An aileron pulse was attempted; however, the vehicle rolled off and a pilot-induced oscillation (fig. 24) resulted even after the normal roll and yaw gains were set. During the oscillation, angles of attack as low as -5° were reached. Opposite aileron did not reduce the amplitude of the oscillation, but increasing the angle of attack to about 8° resulted in roll-oscillation subsidence. With the technique of neutralizing the ailerons and increasing the angle of attack, control of the vehicle was recovered. Overall pilot rating was 5, since techniques were available to control the vehicle.

An inadvertent evaluation of the effect of high interconnect ratio was made on the first M2-F2 flight (fig. 25). An interconnect ratio of -0.6 was selected for the flight. During the flight the pilot selected a lower interconnect ratio; however, to initiate the final turn to landing the pilot increased the ratio, since he felt the roll control was sluggish. During push-over to low angle of attack prior to flare, the vehicle roll control became too sensitive. The pilot attempted to reduce the interconnect ratio but, instead, increased the ratio and a roll oscillation developed. Flight conditions were $M = 0.48$ and $\alpha \approx 0°$ to $-2°$. Damper gains were 0.6 in pitch, roll, and yaw. As the interconnect ratio was increased, the induced roll oscillation increased in amplitude until a roll angle as large as -100° was reached. With a reduction in interconnect ratio with the damper gains used, the oscillation subsided and the pilot regained normal control.

On the sixteenth flight, during the recovery portion of the final turn to a landing after a push-over to a low angle of attack, another uncontrollable lateral-directional oscillation developed. A time history of the aileron and rudder control motions and the vehicle response in roll and yaw is presented in figure 26. Although only about 50° or 60° of bank angle were recorded by the internal instrumentation, because of an insensitive sensor at angles greater than 45°, the vehicle bank angle exceeded 90° to the right and left. The damping augmentation systems were operative with gains of $K_q = 0.6$, $K_p = 0.2$, and $K_r = 0.4$, and the rudder-to-aileron-interconnect ratio was set at -0.45. The initial flight conditions for figure 26 were $h = 8577$ feet (2614 meters), $M = 0.48$, $\bar{q} = 253$ pounds/foot2 (12,114 newtons/meter^2), and $\alpha = -2.6°$.

Flights had been made previously to low angles of attack, where it was known that controllability was poor. The oscillation was started as the pilot attempted to roll out of the final-approach turn. As the pilot lost control, maximum aileron and rudder control were commanded. The rudder was capable of producing somewhat more than 1° of sideslip per degree of rudder, and that amount of sideslip produced about eight times the rolling moment that could be balanced by the rolling moment of the ailerons. Control was regained by increasing the angle of attack and decreasing the control activity. Although control effectiveness was predicted to be invariant with angle of attack, static directional stability increased with angle of attack so the vehicle became more controllable at the higher angle of attack. Even though control was regained, this oscillation and other distractions contributed to a gear-up landing in which the vehicle was extensively damaged.

The flight envelope covered in terms of angle of attack and rudder-to-aileron interconnect is presented in figure 27 (crosshatched area). Included also are pilot ratings of the lateral controllability of the M2-F2 vehicle with the nominal damper gains of $K_p = 0.4$ and $K_r = 0.6$. In normal flight, a range of angle of attack of -2°

to 12° was covered with interconnect ratios at -0.5. Included also are the predicted lateral-control problem areas from figure 22. The predicted lateral-control reversal was verified at two angles of attack, approximately 1° and 7°, with $K_I = -0.2$. The closed-loop lateral instability at low angles of attack was verified at medium and high interconnect ratios. The controllability problem areas were as predicted and were rated at least unacceptable by the pilots. The interconnect ratio of -0.5 selected for use over the normal range of angle of attack was rated by the pilots to be satisfactory for the M2-F2 flight test mission.

Pilot Evaluations

Evaluations of the longitudinal and lateral handling with normal damper gains and interconnect ratios are summarized in table IV for the first flights of the four program pilots. Included also are the vehicle damper gains and interconnect ratios used and angle-of-attack and average Mach number range covered during the phase of the flight being rated. The first-flight ratings were summarized, since these flights had identical flight plans. Each piloting task was the same. However, first-flight pilot ratings should be viewed with some reservations, since the flight exposure at any one flight condition was extremely short and the M2-F2 flight characteristics were unusual compared to a high-performance operational airplane. The pilots were, however, thoroughly familiar with the vehicle characteristics from many hours of M2-F2 flight simulation.

Average pilot rating for longitudinal control was about 2.0, with a range of less than ±1 rating. Lateral-directional control was rated about 3.0, with a range of about ±1.5 rating. Lateral control was, in general, rated poorer (higher pilot rating) than was the longitudinal control.

Two of the pilots had more flight experience in the M2-F2 than the other two. To determine if greater familiarity with the vehicle would alter the pilot ratings, the ratings of these two pilots are presented in table IV for the piloting tasks that were similar to the first-flight tasks. Comparison with the averages presented for the first flights showed only slightly poorer ratings.

The longitudinal transient due to gear extension degraded the longitudinal characteristics at landing to a 5.0 rating. During one of the flights, the pilot had difficulty keeping the vehicle trimmed laterally, and rated the lateral trimmability 6.0, which was much lower than the average rating for lateral control. Lateral trim was through the rudder. Low lateral control power at low landing speeds was recognized early in the program and was rated 5.5, barely acceptable but unsatisfactory.

Approach and Landing

Approach. – Since one advantage of a lifting reentry vehicle is its capability to be flown to, and landed at, a selected location, one flight was made to simulate the terminal maneuver of a mission vehicle. The vehicle was launched to the side and up range of the intended landing site and a 360° overhead approach to a landing was made (fig. 28). A time history of the flight, with some of the events indicated, is shown in figure 29. Although the flight was monitored by radar and escort airplanes provided backup guidance and support as required for safety, the pilot maneuvered the vehicle with only visual reference to the landing area.

Following launch, the first 180° of the approach pattern was flown at about 220 knots (113 meters/second). The pilot indicated that approach pattern control was mechanical during the first 90° of the turn. The planned 180° point was observed visually without assistance from the ground. The M2-F2 nose window was not satisfactory for pattern positioning, since the depression angle was small and visual check points were blocked from view early in the approach pattern; however, roll could be used to check visual reference points. During the turn, the roll- and yaw-damper gains were turned to zero and the interconnect ratio remained at -0.5 to enable an evaluation of the vehicle's basic lateral control. Without roll and yaw augmentation, bank-angle control was not as precise as desired, but turns could be made. The vehicle was susceptible to pilot-induced oscillations. Lateral stick pulses were effective in changing bank angle. At low-key position, roll- and yaw-damper gains were returned to 0.4 and 0.6, respectively, and the pitch-damper gain was turned to zero. To the pilot, the vehicle appeared to be less damped than during pulse stability maneuvers with the dampers at zero. The impression probably resulted from having more time to evaluate the longitudinal characteristics. Nudging the vehicle proved to be an effective control technique rather than driving it around, as was possible with dampers operative.

In general, the overhead approach and landing were made very much as planned with minimal assistance from the ground controller and escort pilots.

The adequacy of the external visibility of the M2-F2 cockpit during the initial part of the overhead approach was rated 4.0; however, for final approach, visibility was rated 2.5.

Landing. – The first flight for the first pilot and the second flight for another pilot are shown in figures 30(a) and 30(b) to further illustrate the flare and landing of the M2-F2. In general, for all flights, rate of descent was high, some 12,000 to 15,000 feet per minute (3657 to 4572 meters per minute), and flight-path angles were approximately -30°. Flare was accomplished at from 280 knots to 310 knots (144 meters/second to 159 meters/second) indicated airspeed. After flare at near level flight, the landing gear was lowered and the vehicle was flown above the ground until the desired landing conditions were met. Landing speeds ranged from 155 knots to 210 knots (80 meters/second to 108 meters/second). The rocket engine was provided for landing safety, and, when used, the rocket thrust appeared to suppress the transients normally associated with the extension of the landing gear. Fourteen flights were made without the aid of, or necessity for using, the landing rocket. The effectiveness of the landing rocket was evaluated on one flight, and the pilot attempted to use the landing rocket during the emergency on flight 16.

With the methods developed to land other research aircraft and with the aid of the escort pilots and flight monitors, there have been no problems in judging flare initiation and landing point within a mile of the desired spot under normal research flight conditions. The flights were planned and monitored to position the M2-F2 for a landing at the runway 2-mile marker. The pilot actually only made judgments directly affecting the landing spot during the time from the final turn to the touchdown. With this technique, normal landings were made within 1 mile of the intended touchdown point.

During flight 16 the pilot did not flare with sufficient altitude to lower the landing gear as the result of a lateral-control problem (fig. 26) during the approach and other distractions during the flare.

During the approach-mission flight, about 1.9g were used to flare the M2-F2; however, the vehicle was capable of greater than 3g at 300 knots (154 meters/second), so more flare capability was available than required. After flare during final approach to landing, roll-control capability was about 15 deg/sec, which was somewhat less than desired for a small maneuverable vehicle. One pilot considered the lateral control at this condition to be marginal. Compounding the problem for the pilot was the high roll effectiveness of the rudder through the roll due to sideslip. One landing was made in a 10-knot (5.1-meter/second) crosswind; however, the lateral control would probably be inadequate for normal operation in crosswinds. With careful attention to flight planning and procedures, the vehicle was operated successfully during 15 research flights. However, the landing task was demanding, requiring unique flight preparation and practice procedures with little margin for error or unusually increased pilot workload. Judgment of flare and landing required complete concentration.

Handling-Qualities Criteria

The handling-qualities criteria are not as well established for lifting-body vehicles as for conventional aircraft; however, proposed criteria for entry vehicles and for high-performance airplanes may serve as a guide for these vehicles for the normal modes of motion if mission requirements are considered. Calculations and simulations of the M2-F2 flight characteristics showed the existence of a lateral phugoid mode (the combination of the roll and spiral modes to form a second oscillatory mode) in some parts of the flight envelope. This mode was predicted to be unstable at negative angles of attack. Since the pilots were closely controlling the vehicle during the 16 short M2-F2 flights, the lateral phugoid has not been identified in flight.

Pilot ratings of the handling of the M2-F2 lifting body were obtained over the limited flight envelope of $M = 0.4$ to 0.7 and covered a range of dynamic pressure of 100 pounds/foot^2 to 300 pounds/foot^2 (4788 newtons/meter^2 to 14,364 newtons/meter^2). The actual flight characteristics of the M2-F2 and the pilot ratings for these characteristics are compared in the following sections with various proposed criteria to indicate the applicability of the criteria to this class of vehicle and, if possible, to assess the handling qualities of the M2-F2.

Longitudinal. – A simulator study conducted for entry vehicles derived a criterion (ref. 11) for handling qualities. Simulated entries were made utilizing X-15, Dyna-Soar, and an early M-1 configuration. The basic vehicle characteristics were varied for pilot evaluation to define regions of desirable handling qualities in terms of vehicle longitudinal and lateral-directional stability and control characteristics. The resulting proposed criteria predict vehicle handling by pilot rating and would be expected to be applicable to the lifting-body vehicle.

The basic M2-F2 for the flight envelope covered was predicted (fig. 31) to be unsatisfactory over much of the flight envelope; however, at the higher dynamic pressures where basic damping was highest, the vehicle was predicted to be satisfactory. This prediction was in fair agreement with the pilots' flight evaluations of about 3. With the pitch damper on at a gain of 0.6, the longitudinal handling was predicted to be, and was rated, satisfactory by the pilots. The range of ratings of the longitudinal characteristics by four pilots was 1.5 to 2.0 for dampers on, and 2.5 to 3.0 for dampers off.

During the entry-vehicle simulation study of reference 11, optimum longitudinal control power was determined for two levels of longitudinal damping. The basic unaugmented M2-F2 longitudinal damping characteristics more nearly correspond to the higher damping values of the proposed criterion. The M2-F2 longitudinal control was predicted to be more sensitive than desired (fig. 32). However, the M2-F2 longitudinal controllability was rated 2.5 to 3 without augmentation at altitude and during flare and landing with dampers operating. The predicted sensitivity was noted by the pilots and was considered to be acceptable for the M2-F2 flight research mission.

The vehicle transient response to landing-gear deployment with dampers on at $K_q = 0.6$, which by plan occurs very near the ground, has been rated 5.0, the least desirable of the longitudinal characteristics. These ratings were probably influenced by the urgency of the impending landing and the proximity to the ground. With the landing technique utilized, the highest dynamic pressure and, consequently, high control effectiveness occurred during the flare. The longitudinal control appeared to be sensitive during this part of the flight, and pitch dampers were desired to stabilize vehicle responses.

Lateral-directional. – As previously discussed, the unaugmented M2-F2 vehicle at low speeds has many of the classic aerodynamic control problems; however, simple aerodynamic dampers and a rudder deflection proportional to aileron deflection interconnect provided satisfactory stability and control for the pilot in some parts of the flight envelope. With a yaw damper set at a gain of 0.6, a roll damper with a gain of 0.4, and the rudder-to-aileron-interconnect ratio at -0.5, the lateral-control characteristics of the M2-F2 were rated by the pilots from 3 to 4.

Another study (ref. 12) considered the effect of lateral-control coupling on the lateral-directional handling qualities of simulated entry vehicles. The handling qualities of entry-vehicle characteristics were evaluated in flight in a variable-stability airplane with visual- and instrument-flight handling-qualities tasks. The M2-F2 handling-qualities evaluations are compared with some of the applicable results of reference 12 in figure 33. Although the range in characteristics covered in the referenced program was not great enough to compare directly with the M2-F2 flight evaluation data, the trends were in fair agreement.

The results of a recent, more general, handling-qualities study (ref. 13) predict pilot ratings for a wide range of handling-qualities parameters representing many configurations and missions. The results of the referenced study (fig. 34) predicted the M2-F2 handling qualities with roll and yaw dampers operative and with rudder-to-aileron interconnect to be generally satisfactory (crosshatched area). Without an interconnect, the response to aileron control was reversed and so was predicted to be uncontrollable with normal controlling techniques. Actual pilot ratings of the lateral-directional handling of the M2-F2 with dampers and interconnect ranged from about 2 to 4.5. The average pilot rating for the pilots with five flights was 3 to 4, which is in fair agreement with the predicted pilot ratings of reference 13.

CONCLUDING REMARKS

Based on flight data and 16 glide flights, the M2-F2 vehicle was statically and dynamically stable in the regions in which it was predicted to be stable. Little variation in apparent stability with Mach number was noted over the limited range of these tests. The control effectiveness of the upper flap was about twice that of the lower flap for pitch control. Measured time to damp was somewhat less than predicted. The flight static-stability and trim results agreed reasonably well with values predicted from wind-tunnel tests.

The handling qualities of the M2-F2 with dampers on and rudder-to-aileron interconnect operative were rated satisfactory by the four program pilots for the lifting-body research mission. There was general agreement between the pilot evaluations and the handling qualities predicted by various proposed criteria. The predicted unacceptable handling characteristics of the basic M2-F2 vehicle were observed in flight.

The vehicle configuration had the lift capability and maneuverability for satisfactory approach and landing from subsonic glide flight at a selected landing spot, but required detailed preparation and practice for the flight and complete concentration during the landing maneuver.

Flight Research Center,
National Aeronautics and Space Administration,
Edwards, Calif., January 26, 1968,
727-00-00-01-24.

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TABLE I. – PHYSICAL CHARACTERISTICS OF THE M2-F2 VEHICLE

Body –	
Planform area, $feet^2$ ($meters^2$):	
Actual	160 (14.9)
Reference, S	139 (12.9)
Longitudinal length, feet (meters):	
Actual	22.2 (6.76)
Reference, c	20.0 (6.11)
Span, without rudder flare, feet (meters):	
Actual	9.63 (2.94)
Reference, b	9.54 (2.91)
Aspect ratio, $\frac{b^2}{S}$, basic vehicle	0.655
Body leading-edge sweep, degrees	77
Lower flap –	
Area, $feet^2$ ($meters^2$)	15.23 (1.41)
Span, feet (meters)	5.42 (1.65)
Chord, feet (meters)	2.81 (0.86)
Deflection, degrees:	
Pilot's control authority, down	5 to 30
Pitch stability augmentation system authority	±5
Upper flaps, two –	
Area, each, $feet^2$ ($meters^2$)	9.57 (0.89)
Span, each, feet (meters)	4.28 (1.31)
Chord, feet (meters)	2.23 (0.68)
Deflection, each flap, degrees:	
Pitch trim (symmetric travel), up	0 to 35
Pilot's aileron authority (asymmetric travel)	±5
Roll stability augmentation system authority (asymmetric travel)	±2 1/2
Vertical stabilizers, two –	
Area, each, $feet^2$ ($meters^2$)	16.10 (1.50)
Height, trailing edge, feet (meters)	3.79 (1.16)
Chord, feet (meters):	
Root	7.36 (2.24)
Tip	2.58 (0.79)
Leading-edge sweep, degrees	62.3
Rudders, two –	
Area, each, $feet^2$ ($meters^2$)	5.27 (0.49)
Span, each, feet (meters)	4.20 (1.28)
Chord, feet (meters)	1.25 (0.38)
Deflection, each (outward), degrees:	
Pilot's effective control authority	12
Yaw stability augmentation system authority	4.2
Weight, including pilot, pounds (kilograms)	6000 (2722)
Center of gravity:	
Percentage of actual length	49
Percentage of reference length	54
Planform-area loading, $\frac{W}{S}$, pounds/$foot^2$ (kilograms/$meter^2$)	43.2 (196)
Moments of inertia –	
I_X, slug-$foot^2$ (kilogram-$meter^2$)	956.3 (1296)
I_Y, slug-$foot^2$ (kilogram-$meter^2$)	5583 (7570)
I_Z, slug-$foot^2$ (kilogram-$meter^2$)	6005 (8142)
I_{XZ}, slug-$foot^2$ (kilogram-$meter^2$)	-417 (-565)

[redacted]

TABLE II. – RANGE OF THE RECORDED QUANTITIES AND THE UNITS IN WHICH THEY WERE RECORDED

Longitudinal stick position, inches (centimeters) –	
Forward	4.5 (11.4)
Aft	4.9 (12.4)
Lateral stick position, inches (centimeters) –	
Right	2.9 (7.4)
Left	2.7 (6.9)
Rudder-pedal position, inches (centimeters) –	
Right	2.9 (7.4)
Left	3.2 (8.1)
Angle of attack, degrees	-10 to 30
Angle of sideslip, degrees	±10
Rolling velocity, degrees/second	±60
Pitching velocity, degrees/second	±40
Yawing velocity, degrees/second	±40
Pitch attitude, degrees –	
Flights 1 to 15	-30 to 60
Flight 16	±60
Roll angle, degrees	±90
Normal acceleration, g	-1 to 3
Lateral acceleration, g	±1.0
Longitudinal acceleration, g	±2.0, ±0.5
Upper-flap position, degrees	10 to -45
Lower-flap position, degrees	0 to 35
Interconnect ratio	0 to -1.0*
Rudder position, degrees	0 to 45

*Linear extrapolation possible.

[redacted]

[redacted]

TABLE III. - MODIFIED COOPER PILOT RATING SCALE USED DURING THE PROGRAM

General classification	Numerical rating	Adjective	Handling qualities	Ability to complete mission	Ability to land
Satisfactory	1	Excellent	Easy to control precisely - little corrective control required.	Yes	Yes
	2	Very good	Good response but necessitates attention for precise control.		
	3	Good	Acceptable controllability but more than desired attention generally needed.		
Unsatisfactory	4	Fair	Submarginal for normal use - requires excessive pilot attention.	Yes	Yes
	5	Poor	Controllability poor - demands constant pilot attention and continuous control inputs.	Probably	Yes
	6	Bad	Can be controlled but pilot must exercise considerable care.	Doubtful	Yes
Unacceptable	7	Very bad	Difficult to control and demands considerable pilot concentration.	No	Probably
	8	Dangerous	Controllable only with a high degree of pilot concentration and large control inputs.	No	Doubtful
	9	Very dangerous	Extremely dangerous - can be controlled only with exceptional piloting skill.	No	No
	10	Catastrophic	Uncontrollable.	No	No

[redacted]

TABLE IV. – PILOT EVALUATIONS OF M2-F2 FLIGHTS
[$K_q = 0.6$, $K_p = 0.4$, $K_r = 0.6$, $K_I = -0.5$]

	First flight, four pilots					Five flights	
						Average rating	
	Average rating	Total range of ratings	α, deg	Average M	Average $\bar{q}$, lb/ft^2 (N/m^2)	Pilot 1	Pilot 4
Overall launch recovery task	2.0	0					
Longitudinal attitude control	2.0	1.5	0 to 2	0.61	82 (3,926)	2.5	2.0
Bank and directional control	2.1	0.5				4.0	3.5
Overall rating of flare at altitude	2.0	1.5					
Longitudinal control	1.7	0.5	2 to 8	0.60	200 (9,576)	---	---
Lateral-directional control	3.0	1.5				---	---
Overall rating of 90° turn	2.2	2.0					
Bank-angle control	2.5	2.0	$\approx$ 5	0.58	150 (7,182)	4.0	3.0
Longitudinal control	2.0	2.0				2.5	2.0
Overall rating of high-speed approach	2.3	1.5					
Longitudinal control	1.6	1.0	-2 to 0	0.50	300 (14,364)	2.0	2.0
Lateral-directional control	3.0	1.5				4.0	3.5
Overall landing task	2.8	3.0					
Longitudinal control	2.0	2.0	------	----	--- -------	2.0	2.0
Lateral-directional control	2.5	2.0				3.5	3.0
Overall rating of postflare	2.9	2.5					
Longitudinal control	1.6	1.0	3 to 5	0.36	175 (8,379)	2.5	2.5
Lateral-directional control	2.5	2.0				4.5	3.5

[redacted]

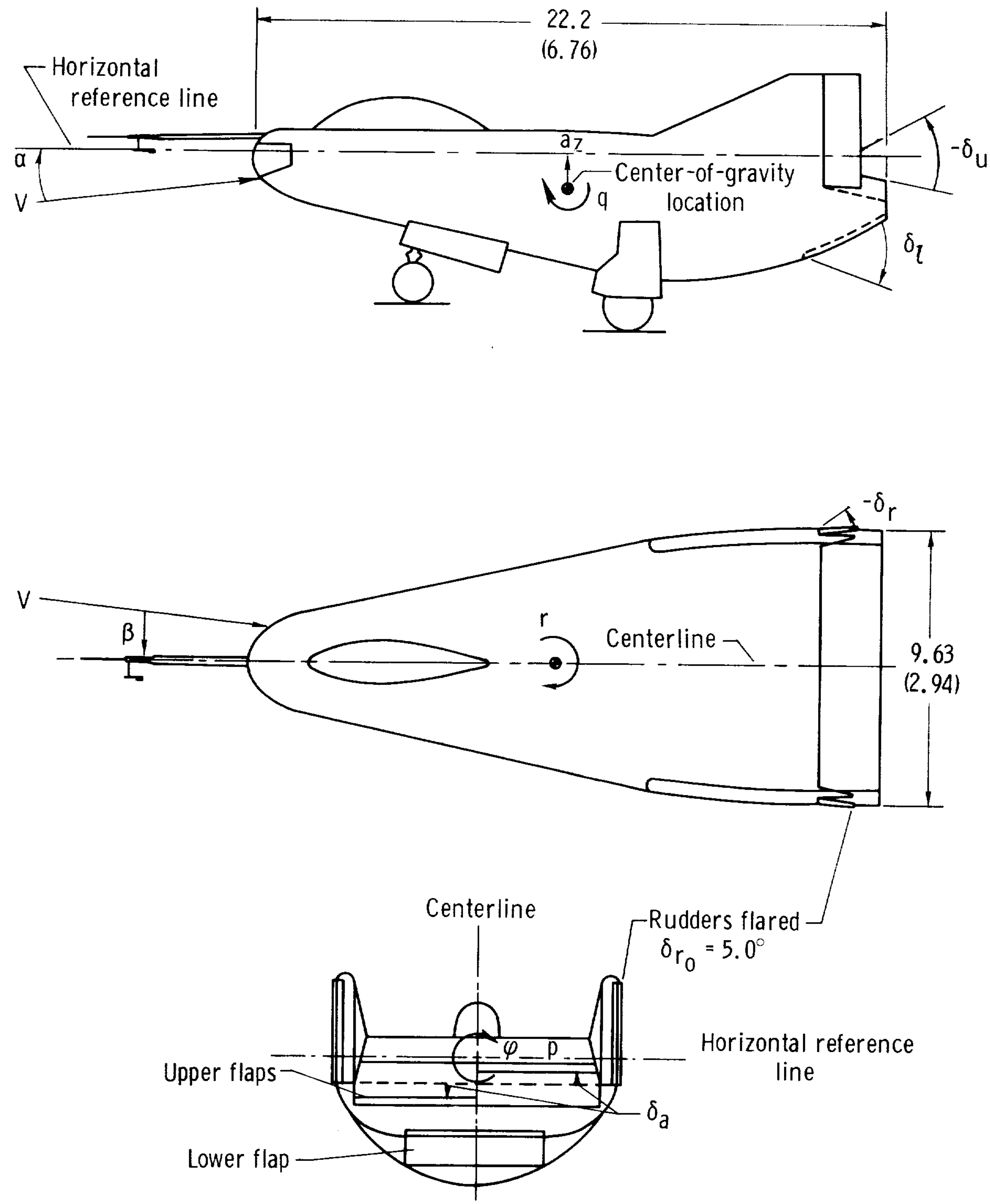
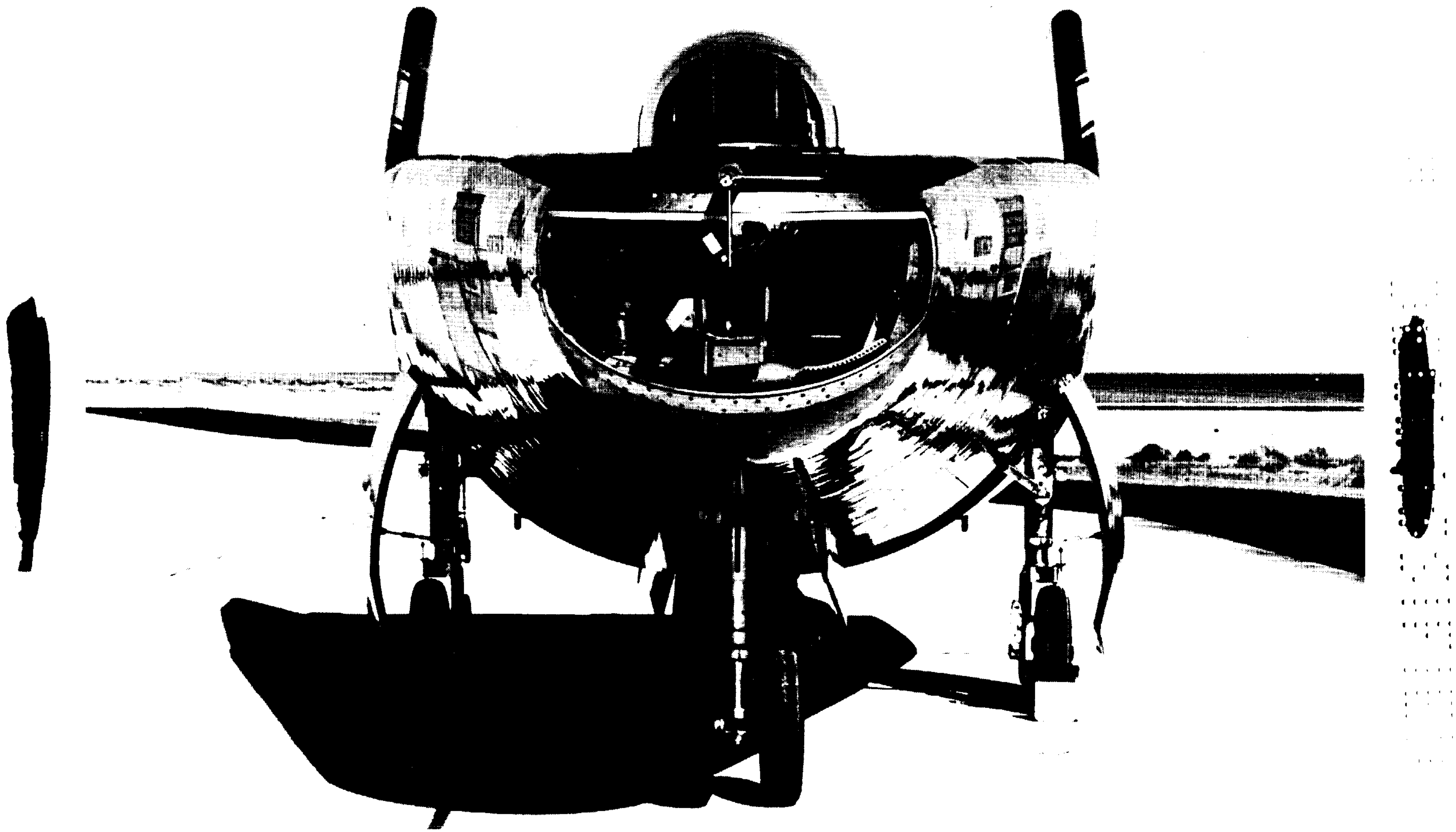


Figure 1.– Three-view drawing of the M2-F2, with the sign convention used. Dimensions in feet (meters) unless otherwise noted. See table I for reference dimensions.

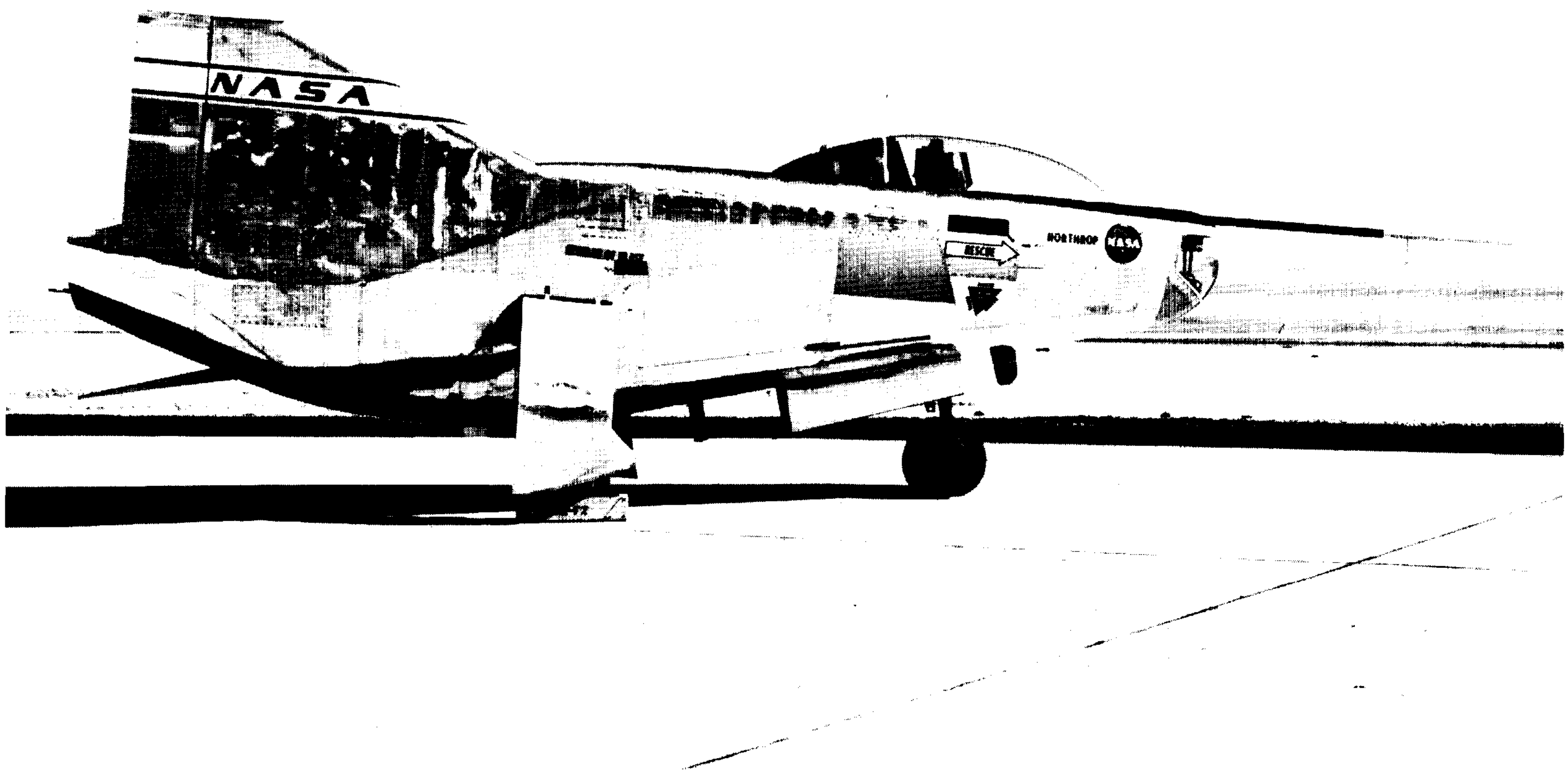
[redacted]



(a) Front view.

E-14338

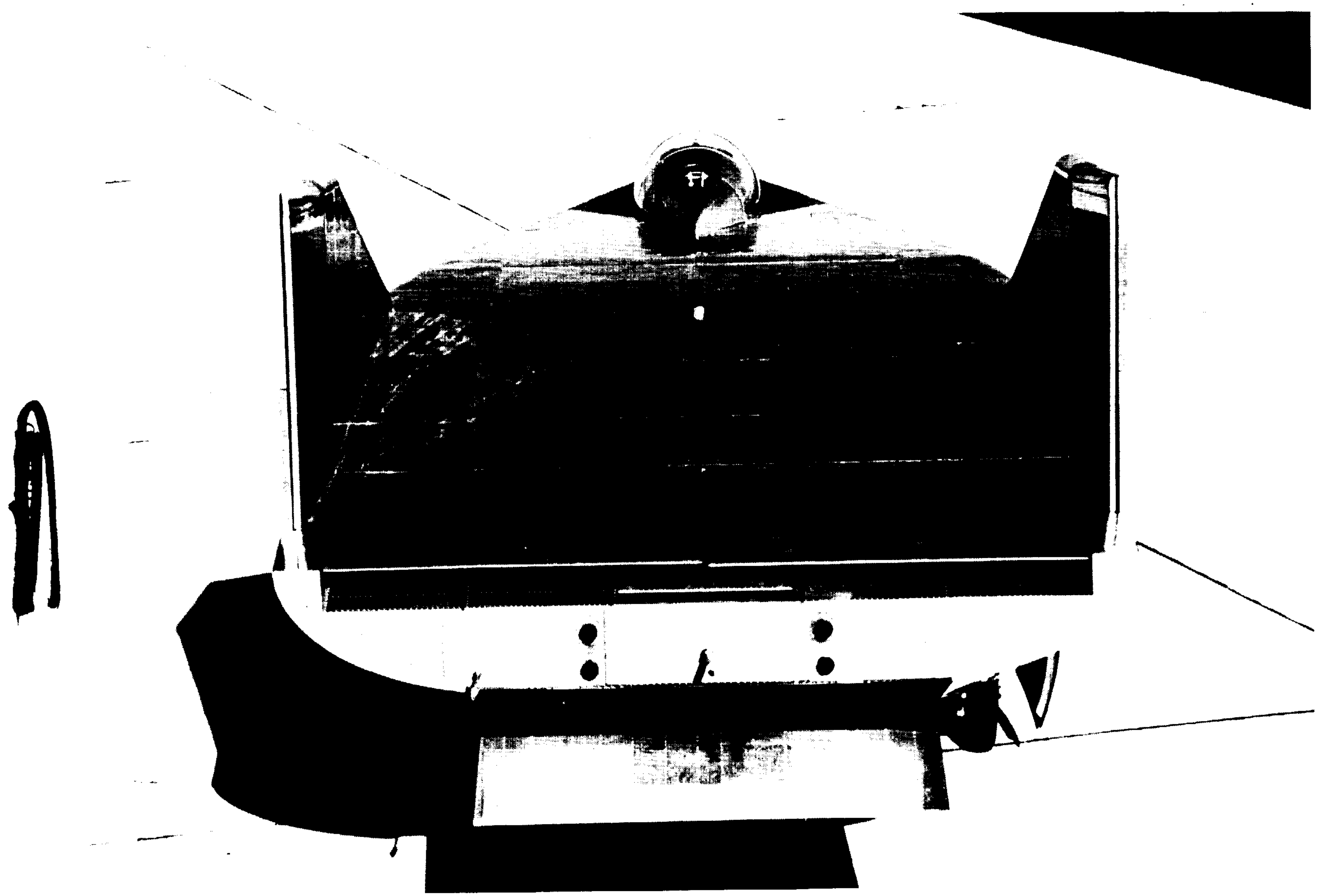
Figure 2. – Photographs of the M2-F2



(b) Right-side view.

E-14333

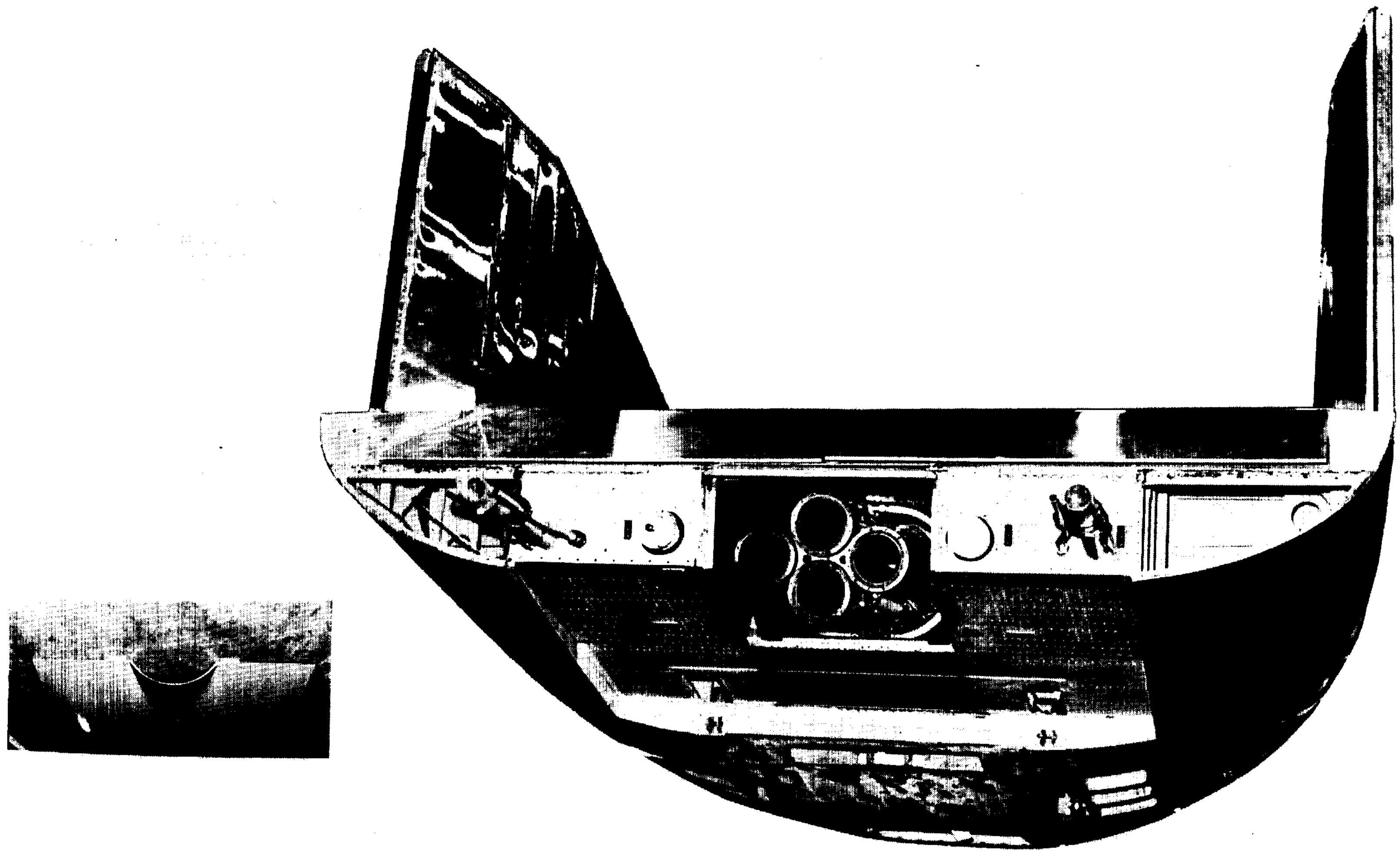
Figure 2. – Continued.



E-14350

(c) Rear view.

Figure 2. - Continued.



(d) Rear view with engine installed. Modified lower flap shown in inset.

Figure 2. – Concluded.

[redacted]

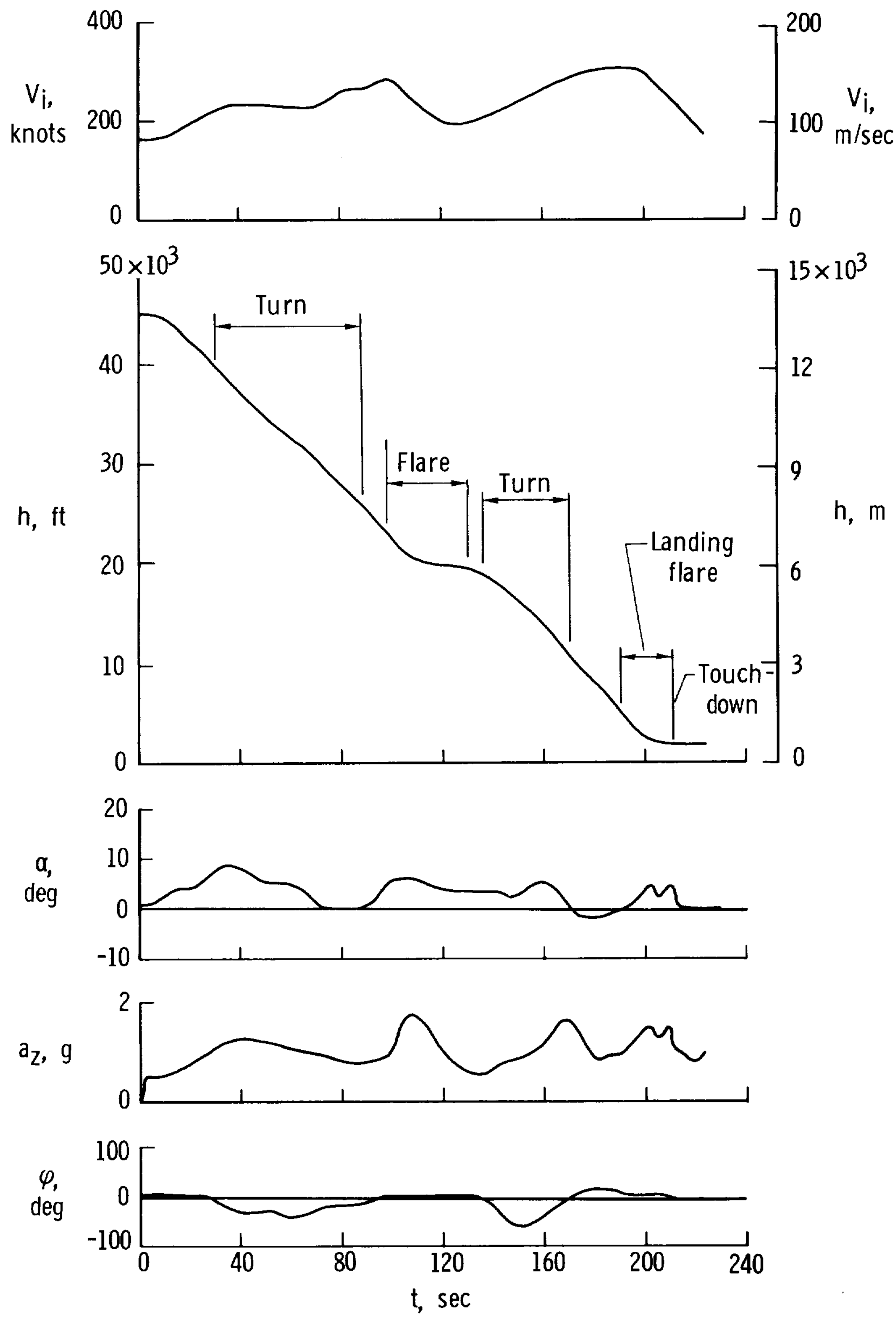


Figure 3. – Time history of a typical glide flight of the M2-F2.

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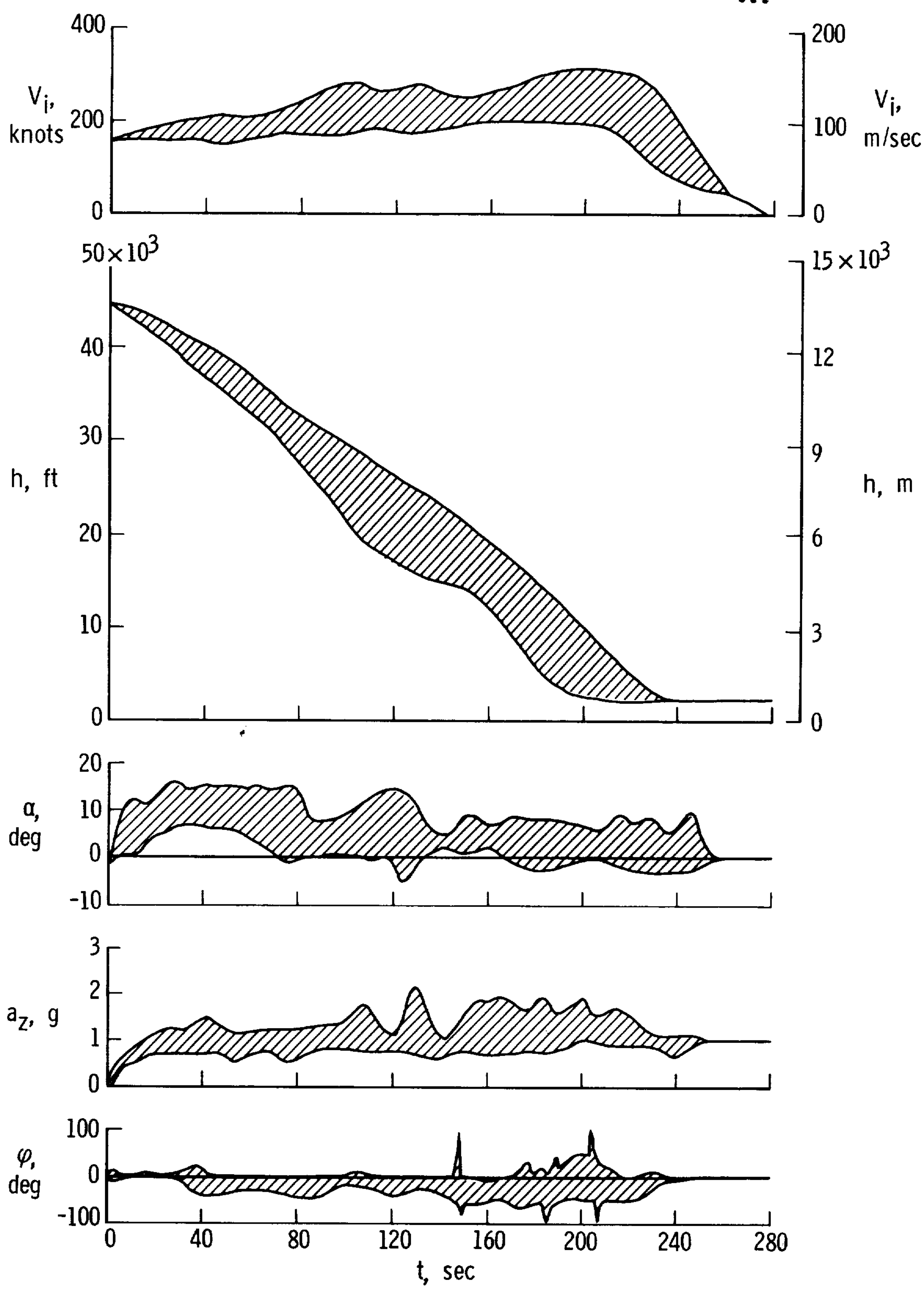

Figure 4. – Flight envelope covered during the 16 M2-F2 flights.

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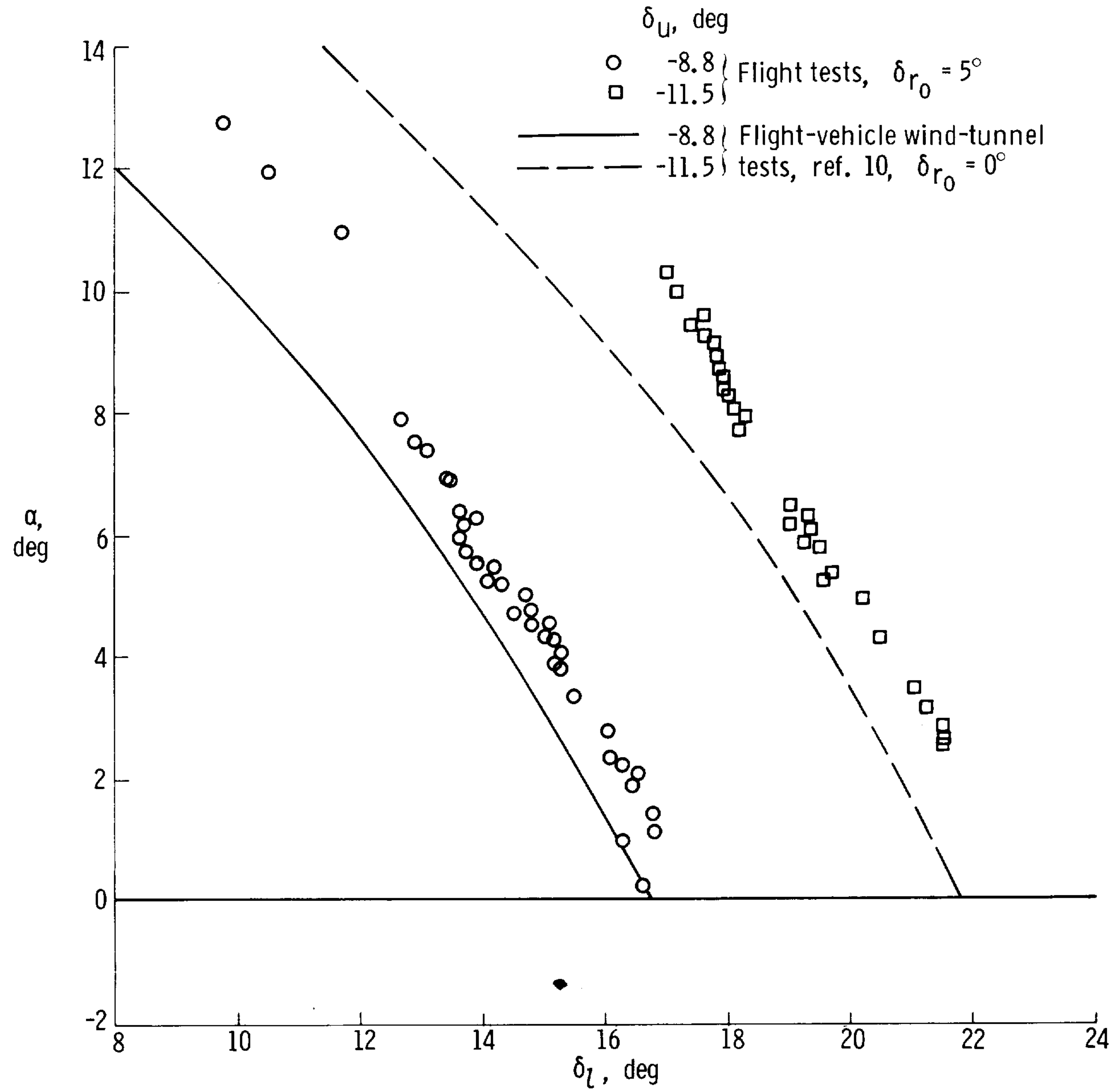
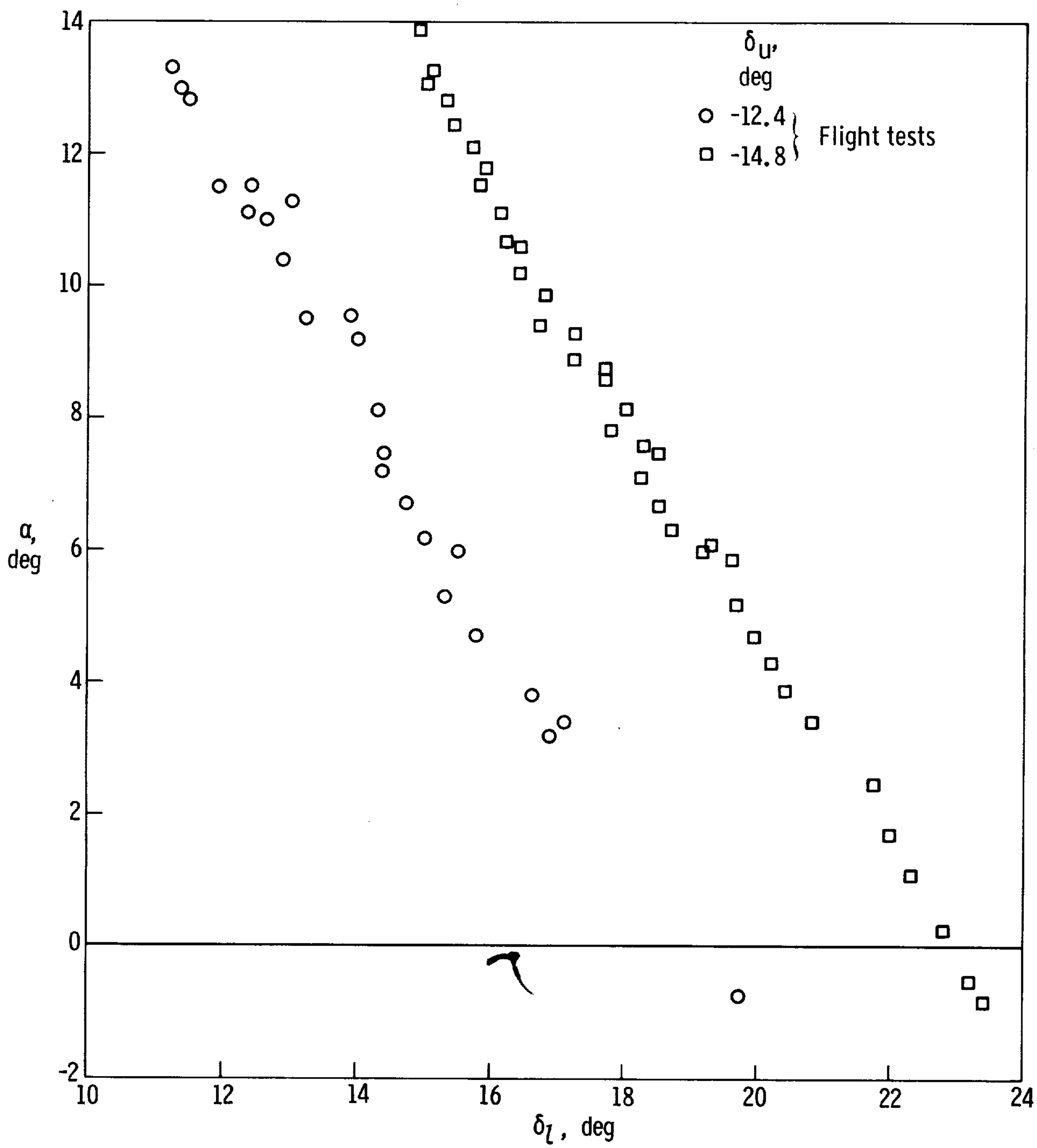


(a) Original configuration, M = 0.4 to 0.7.

Figure 5. – Variation of longitudinal trim with angle of attack for two deflections of the upper pitch flap in the original configuration and in the configuration with the rocket engine installed. Gear up; center of gravity = 54 percent c.

[redacted]



(b) Rocket engine installed, M = 0.4 to 0.6.

Figure 5. – Concluded.

[redacted]

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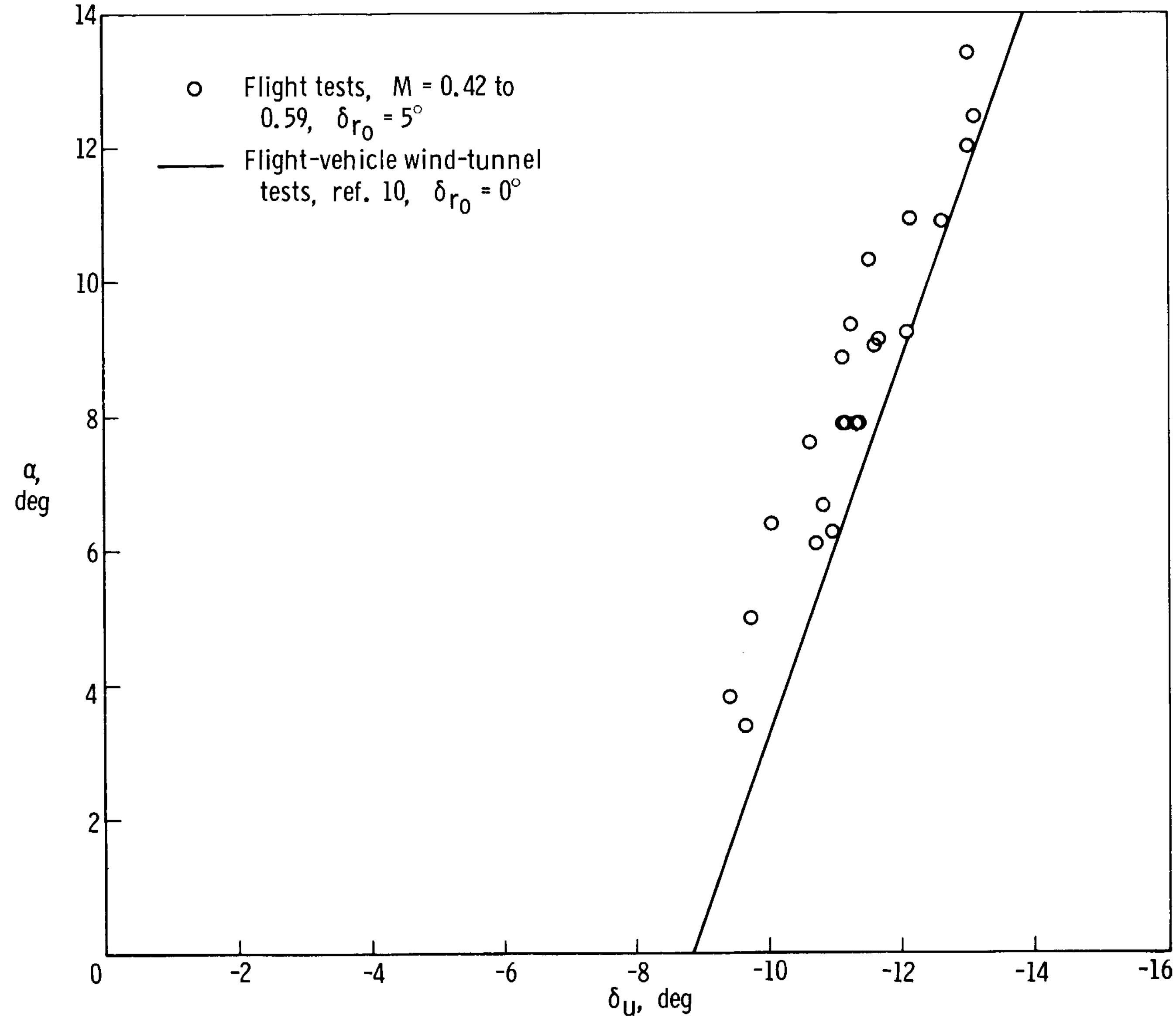

Figure 6. – Angle-of-attack variation with trim upper-flap position. $\delta_l = 17^\circ$; gear up; center of gravity = 54 percent c.

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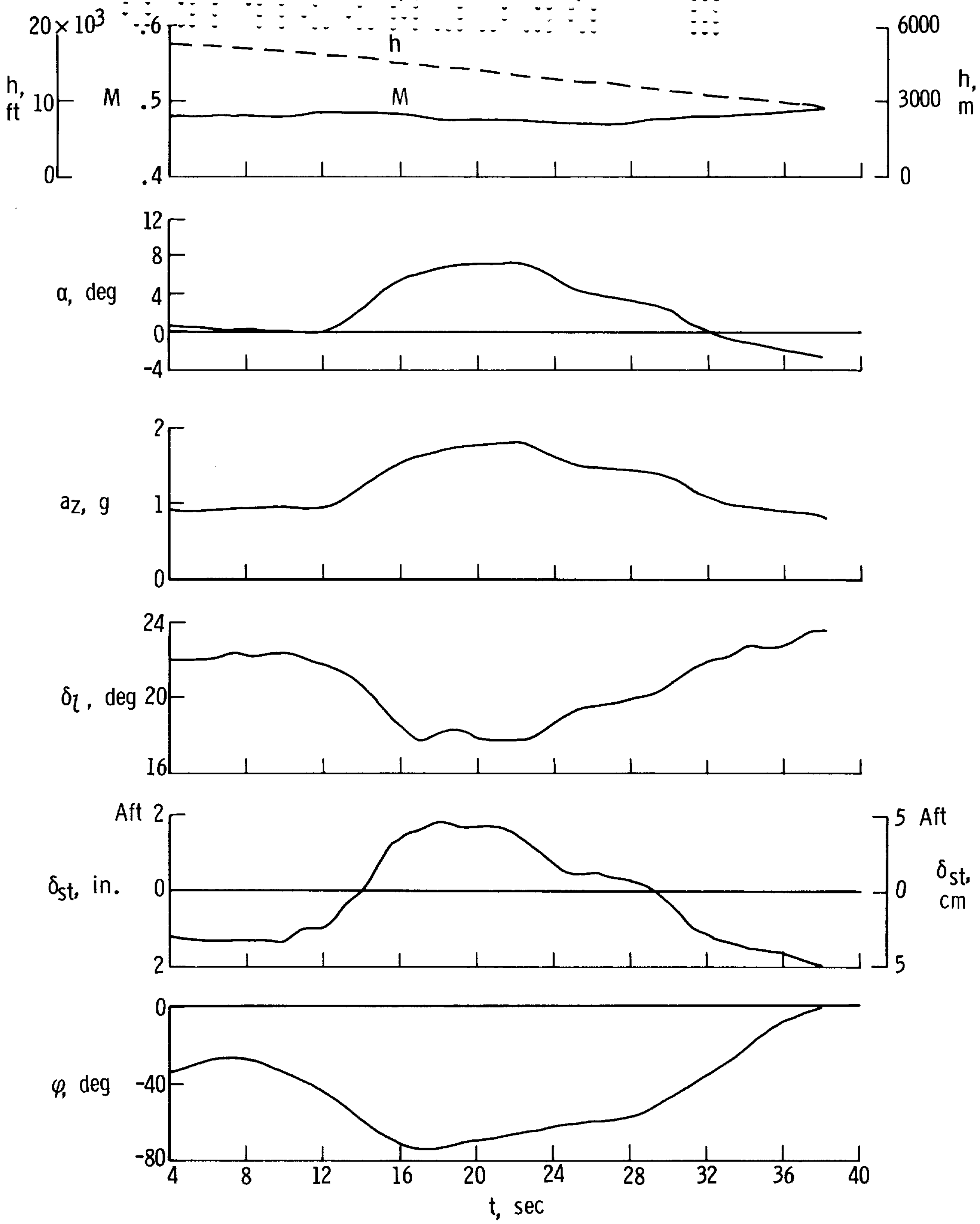

Figure 7. – Typical M2-F2 turn maneuver during glide flight. $\delta_u = -11.2°$; center of gravity = 54 percent c; $K_q = 0.6$; $K_p = 0.4$; $K_r = 0.6$; $K_I = -0.5$.

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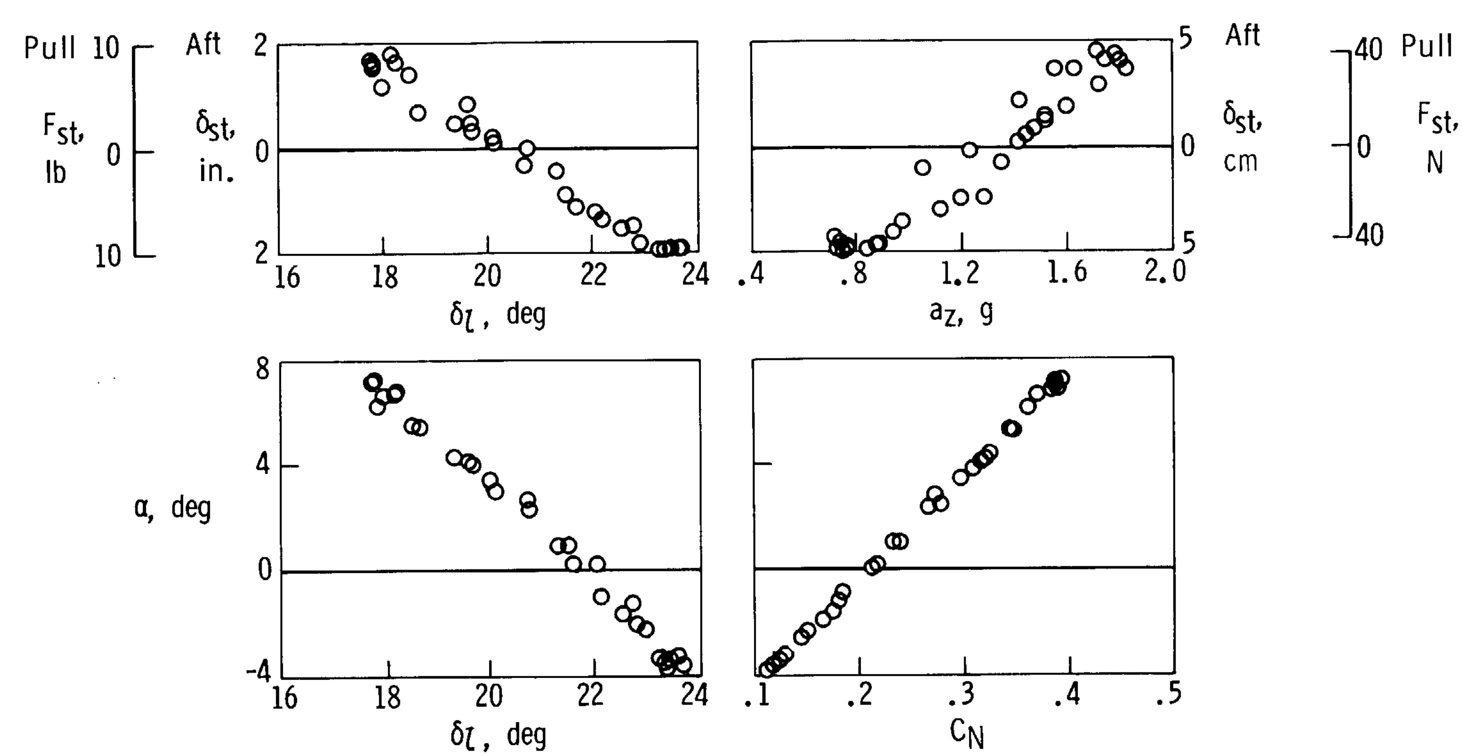

Figure 8. – Apparent longitudinal stability during the gliding turn of figure 7. $M = 0.48$; center of gravity = 54 percent c; $\delta_{r_o} = 5.0°$; $\delta_u = -11.2°$; $K_q = 0.6$; $K_p = 0.4$; $K_r = 0.6$; $K_I = -0.5$.

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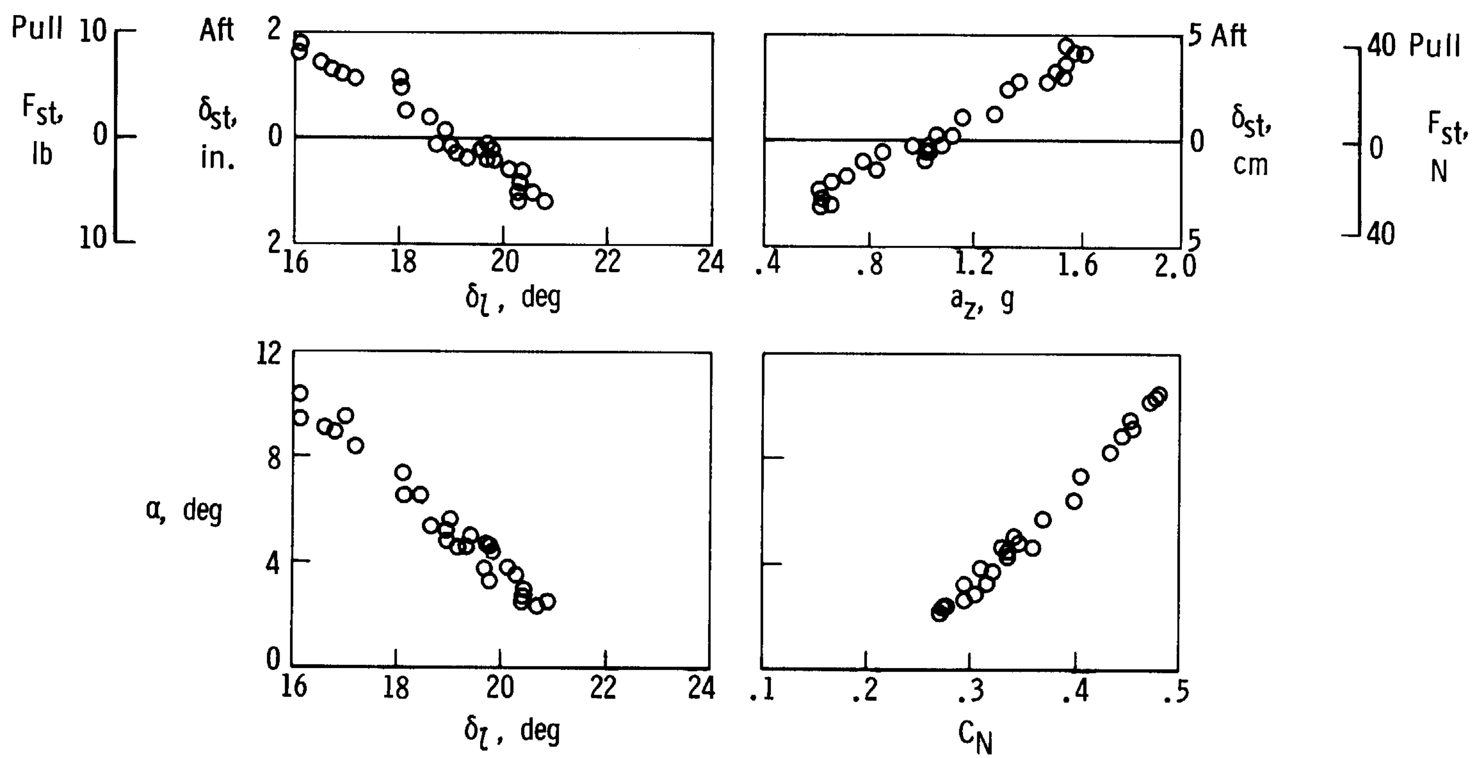

Figure 9. – Apparent longitudinal stability during pullup following launch. $M = 0.64$ to 0.70; $\delta_u = -11.1^\circ$; center of gravity = 54 percent c; $\delta_{r_o} = 5^\circ$; $K_q = 0.6$; $K_p = 0.4$; $K_r = 0.6$; $K_I = -0.5$.

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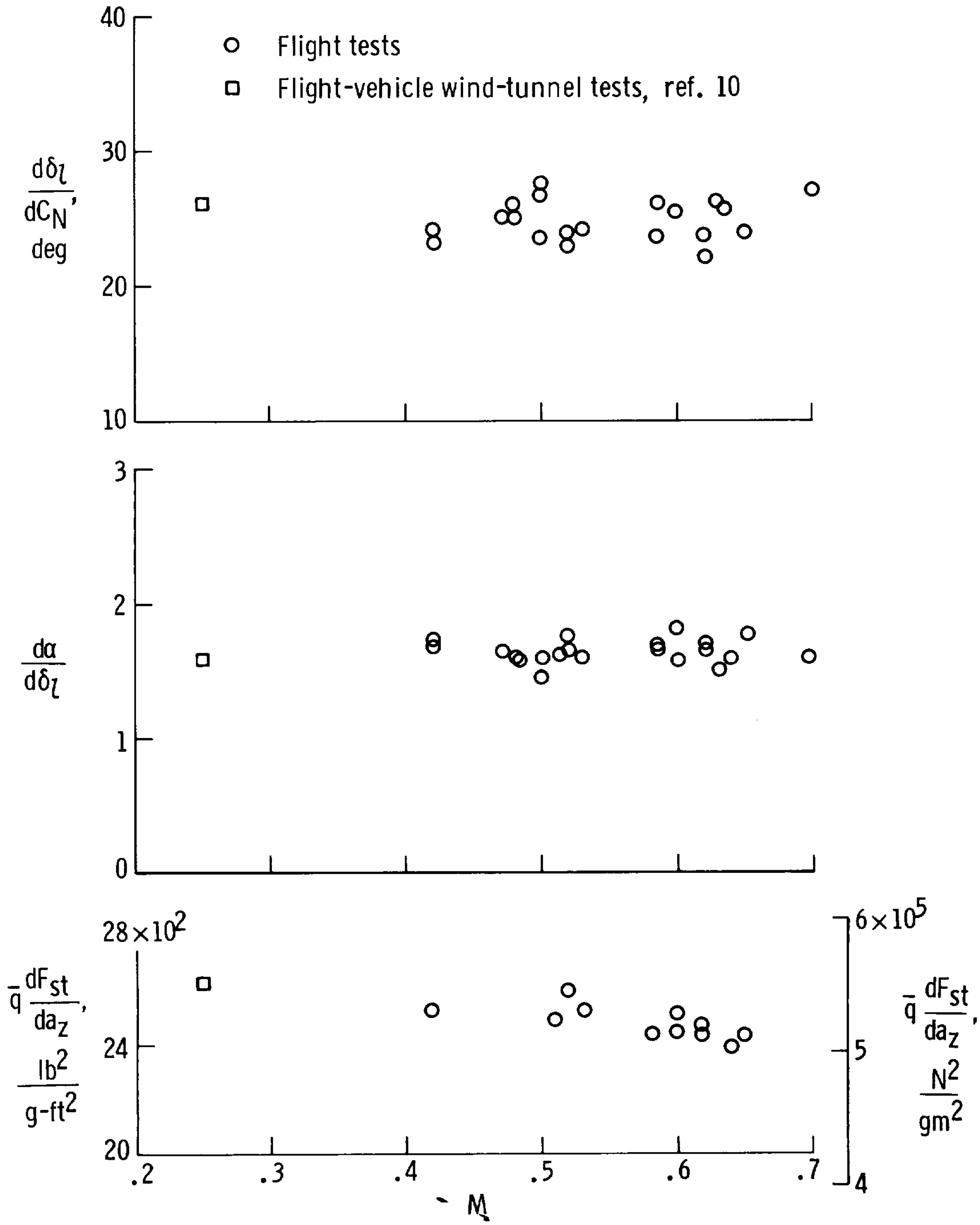

Figure 10. – Variation of apparent longitudinal-stability characteristics with Mach number. Center of gravity = 54 percent c.

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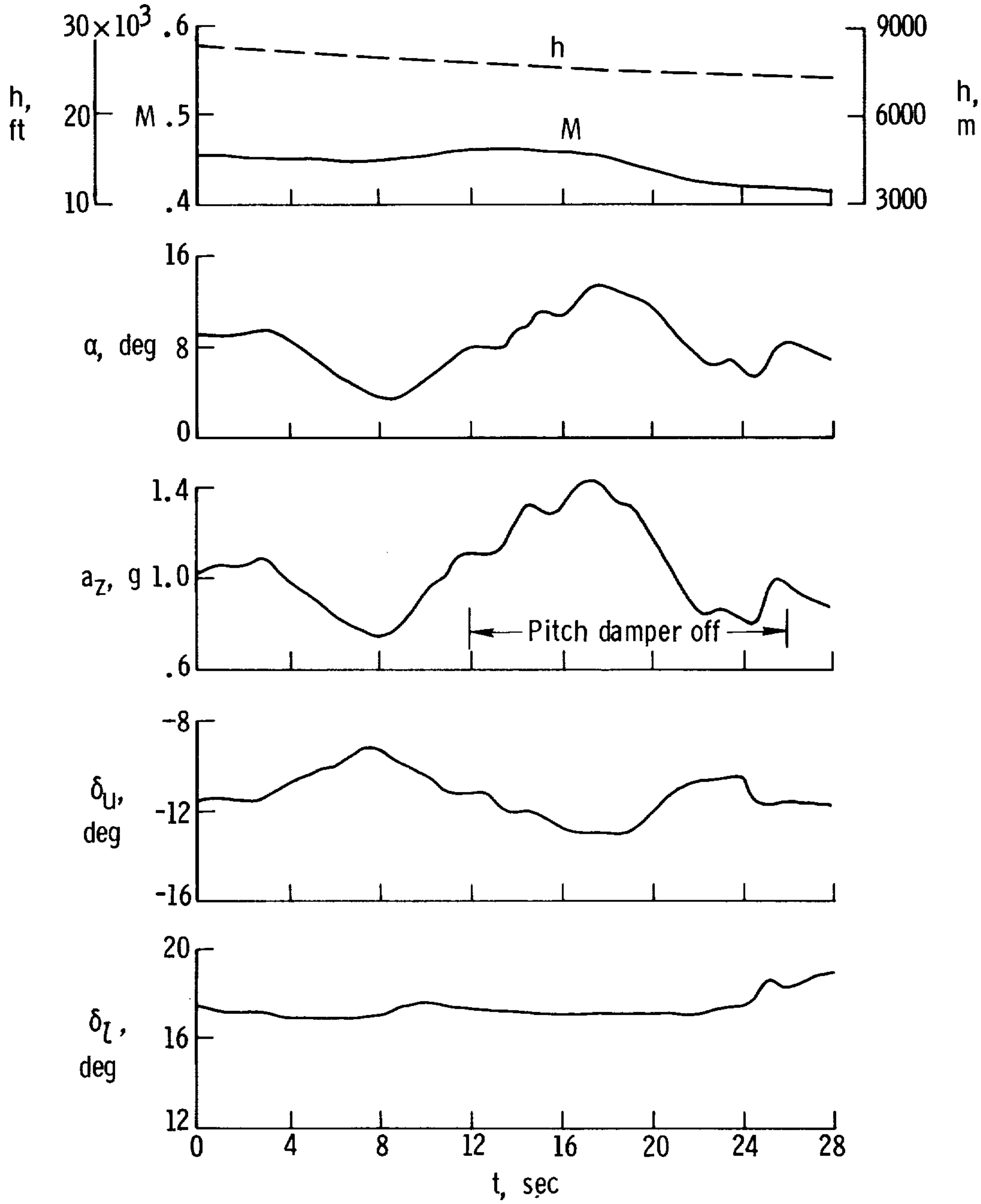

Figure 11. – Time history of an M2-F2 pullup with the upper flap. Center of gravity = 54 percent c; $K_q = 0.6$; $K_p = 0.4$; $K_r = 0.6$; $K_I = -0.5$.

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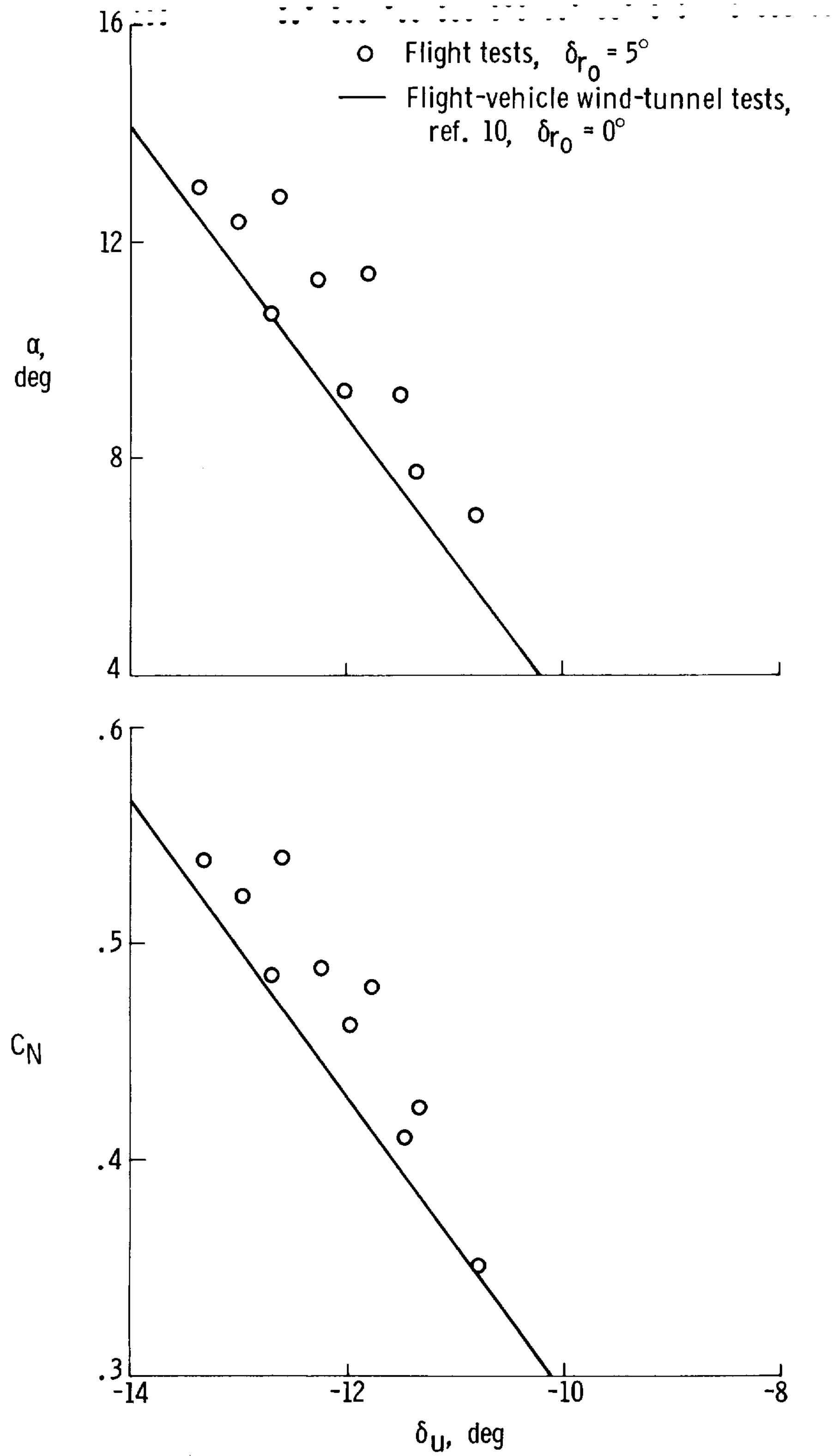

Figure 12. – Apparent maneuvering stability of the M2-F2 with the upper flap, as indicated during the maneuver of figure 11. Pitch dampers off; $\delta_l = 17.5°$.

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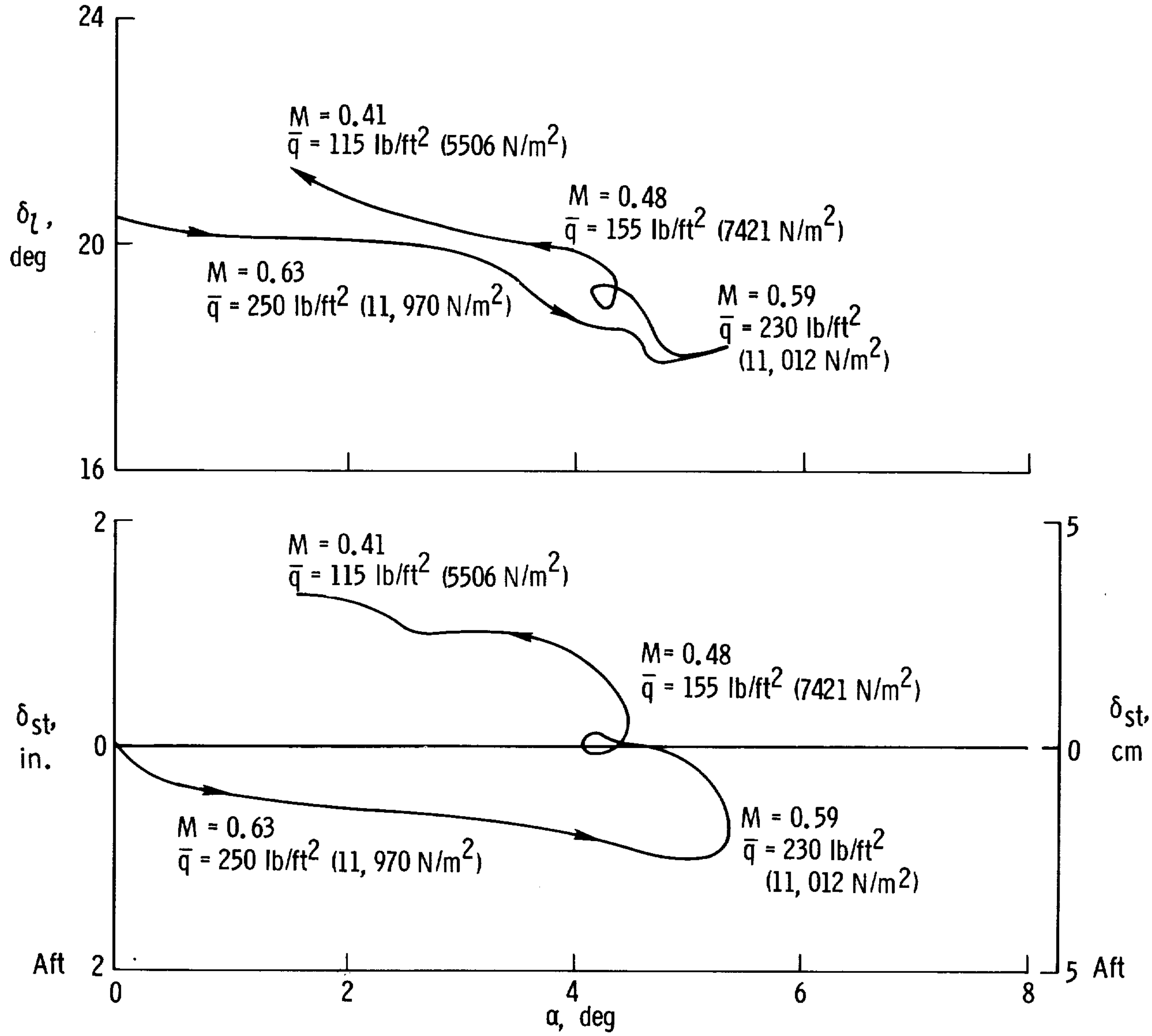

Figure 13. – M2-F2 apparent longitudinal stability during flare at altitude. Gear up; center of gravity = 54 percent c; δ_u = -11.8°; K_q = 0.6; K_p = 0.4; K_r = 0.6; K_I = -0.5.

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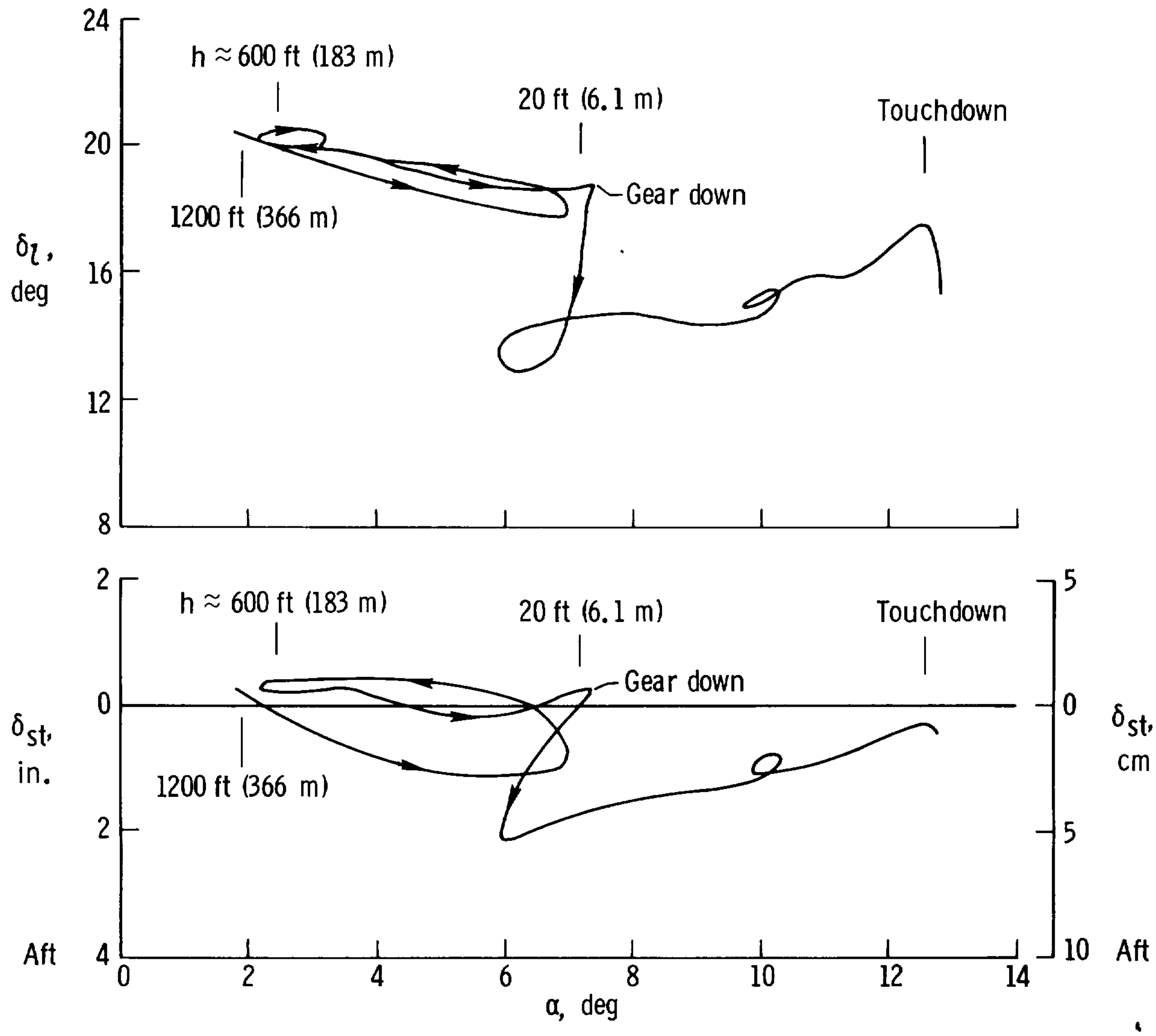

Figure 14. – Typical landing with the M2-F2 illustrating the apparent longitudinal instability. Center of gravity = 54 percent c; $\delta_u = -11.3°$; $K_q = 0.6$; $K_p = 0.4$; $K_r = 0.6$; $K_I = -0.5$.

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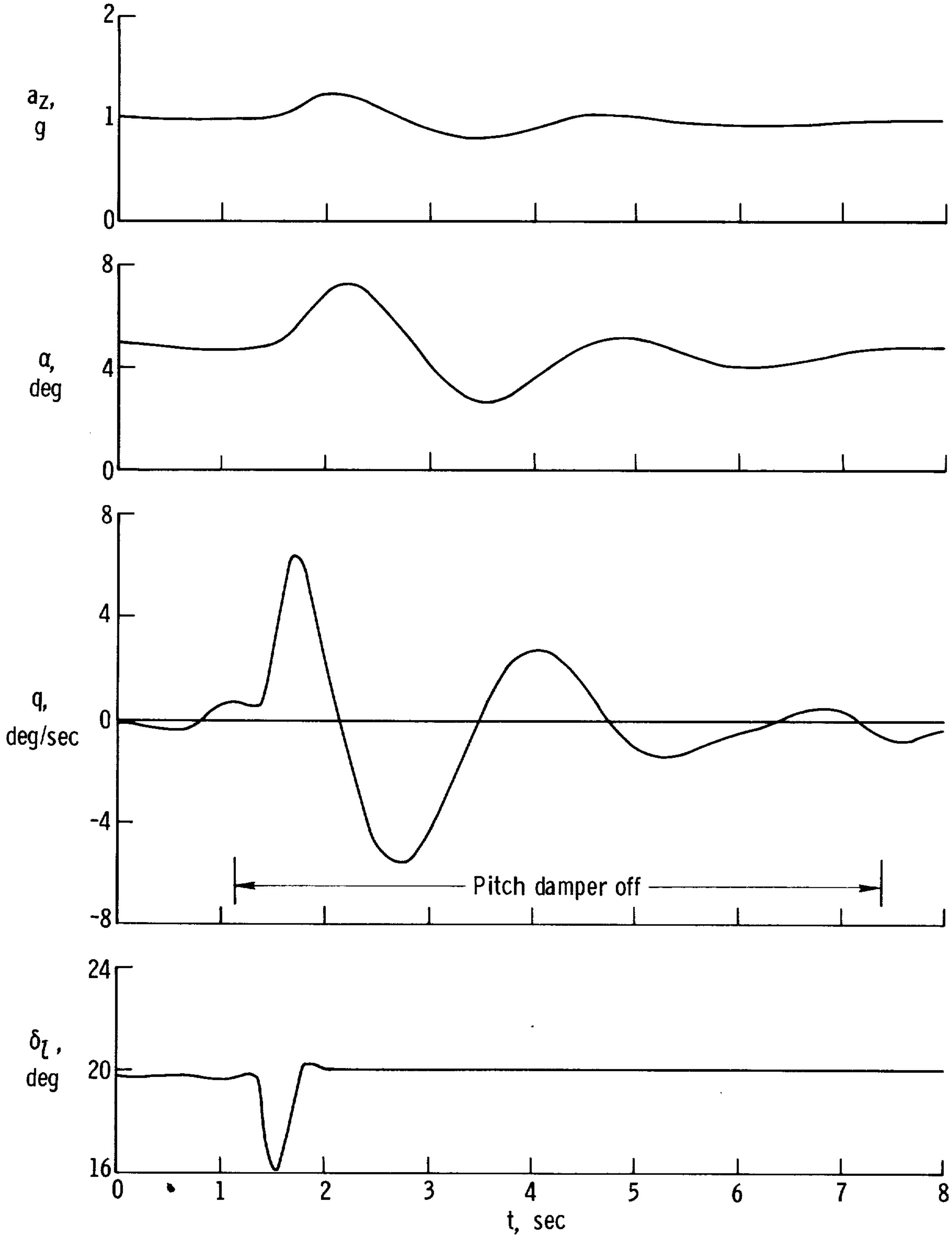

Figure 15. – Time history of the M2-F2 dynamic longitudinal response to a pulse of the lower flap. $M = 0.62$; $h = 37,000$ ft (11,278 m); center of gravity = 54 percent c; $K_p = 0.4$; $K_r = 0.6$; $K_I = -0.5$; $\delta_u = -11.4°$.

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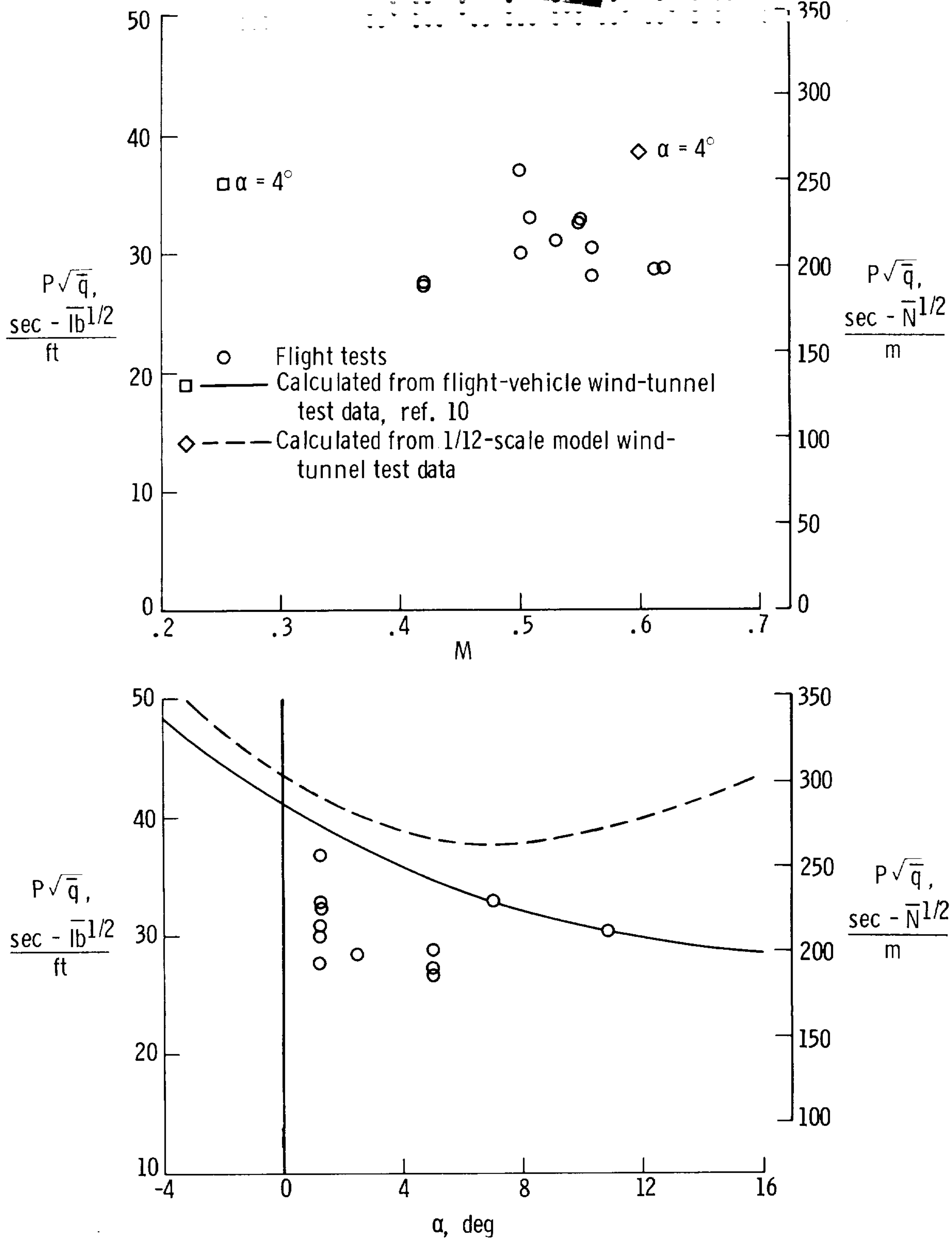

(a) Short period.

Figure 16. - Variation of the M2-F2 dynamic longitudinal characteristics with Mach number and angle of attack and comparison with calculated values based on flight-vehicle wind-tunnel test data. Center of gravity = 54 percent c.

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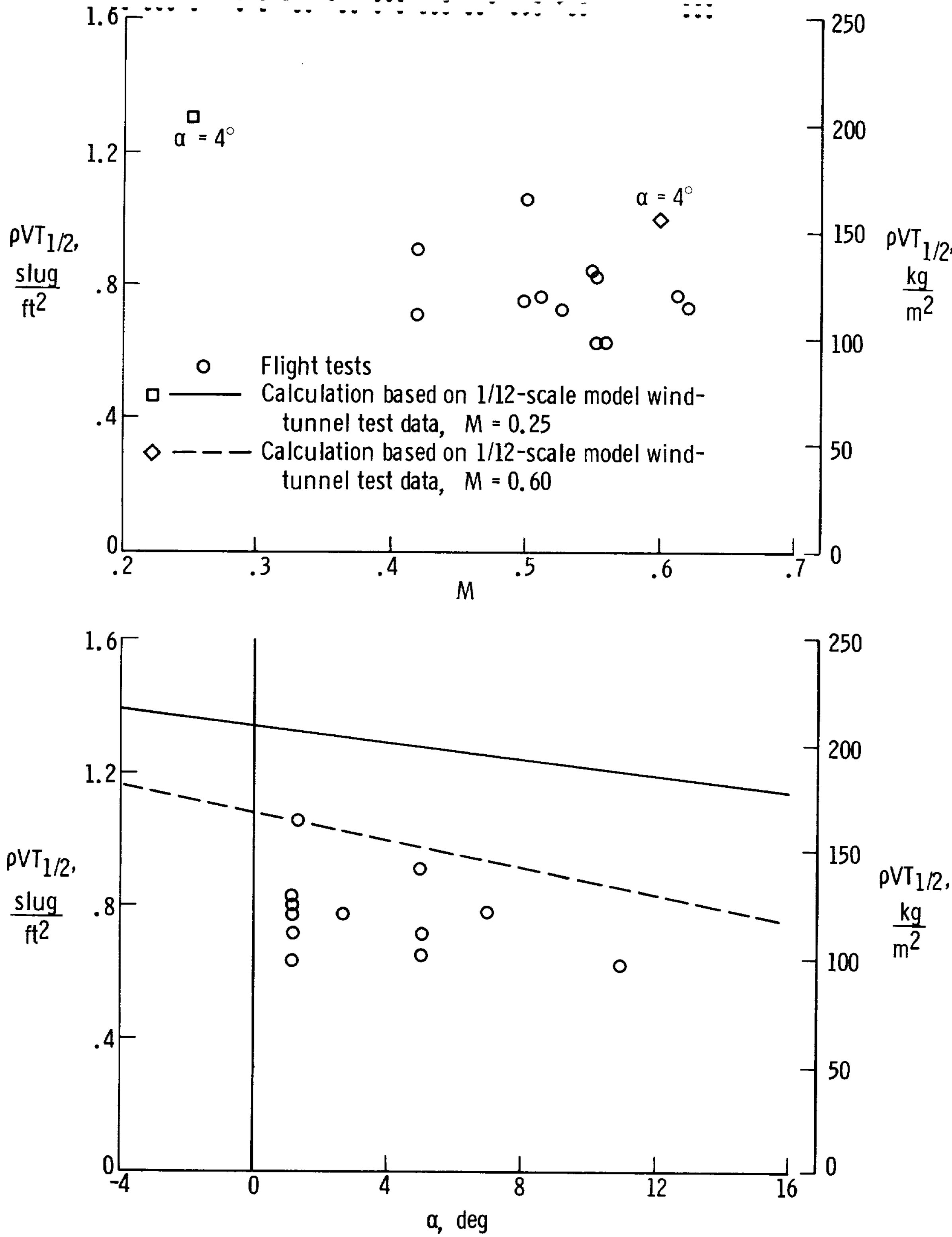

(b) Damping.

Figure 16. — Concluded.

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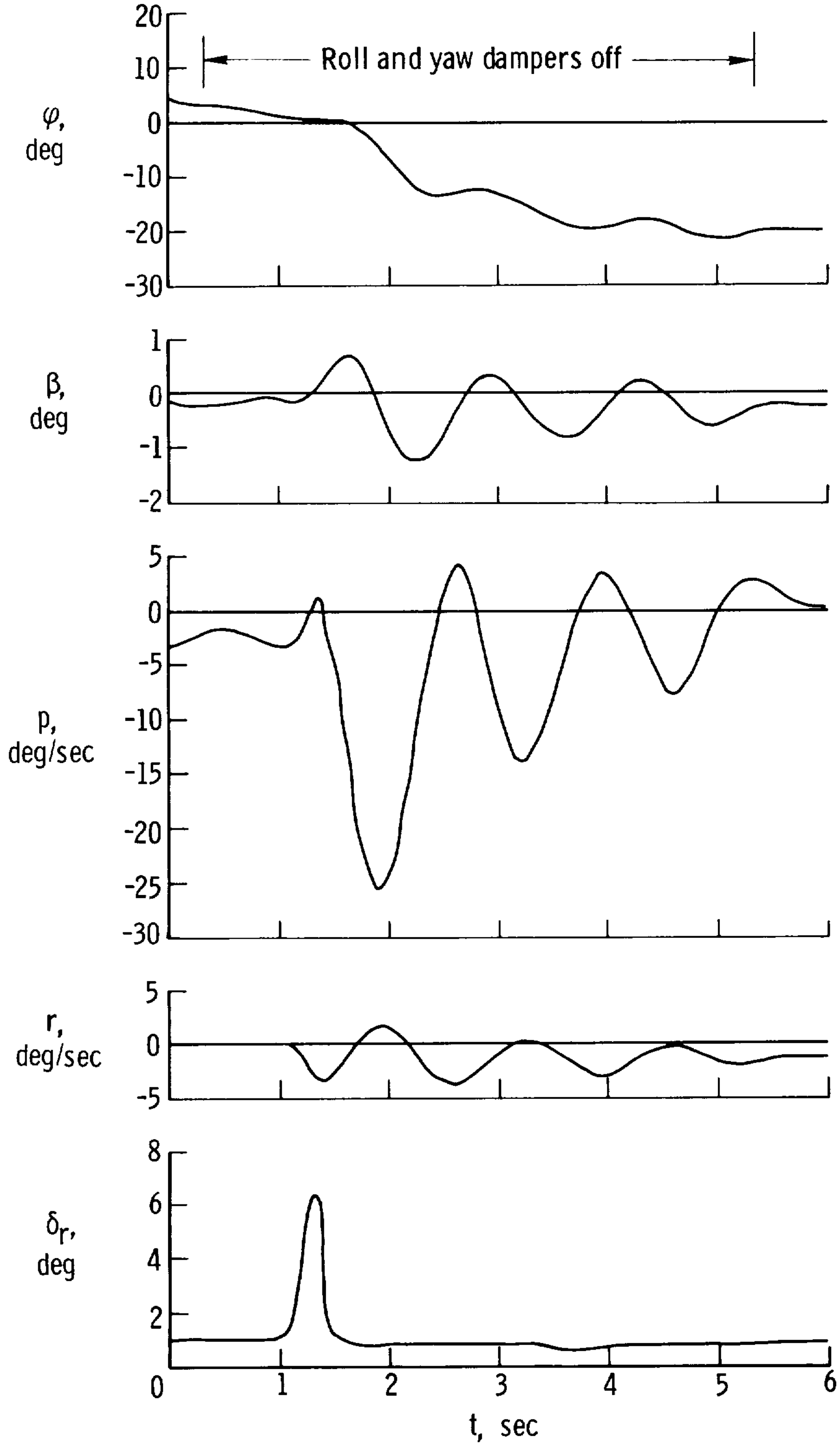

Figure 17. – Time history of the M2-F2 lateral-directional response to a rudder pulse. M = 0.6; h = 35,000 ft (10,668 m); K_q = 0.6; K_I = -0.5.

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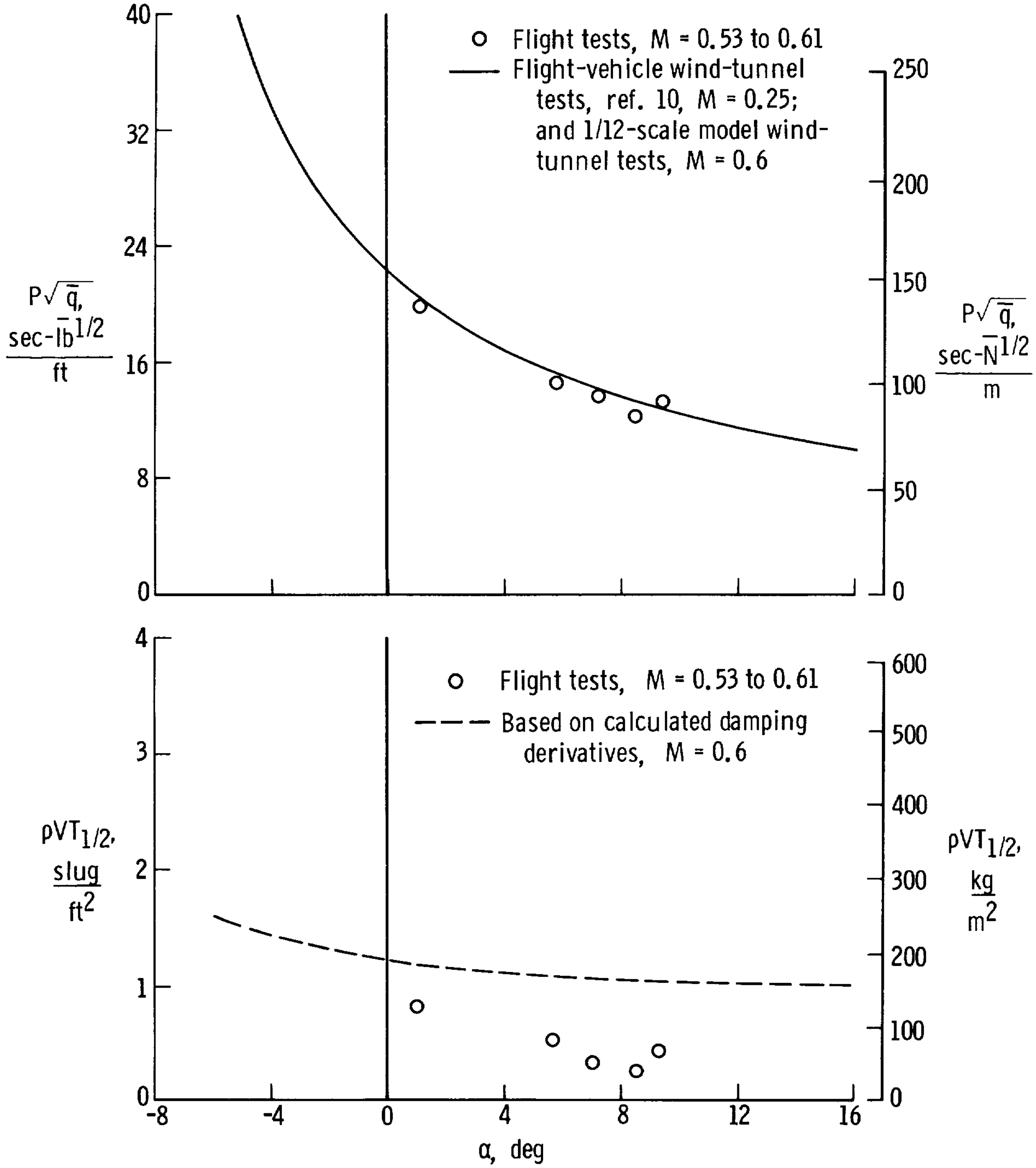

Figure 18. – Variation of the dynamic lateral-directional characteristics of the M2-F2 with angle of attack and comparison with predictions based on wind-tunnel and estimated characteristics.

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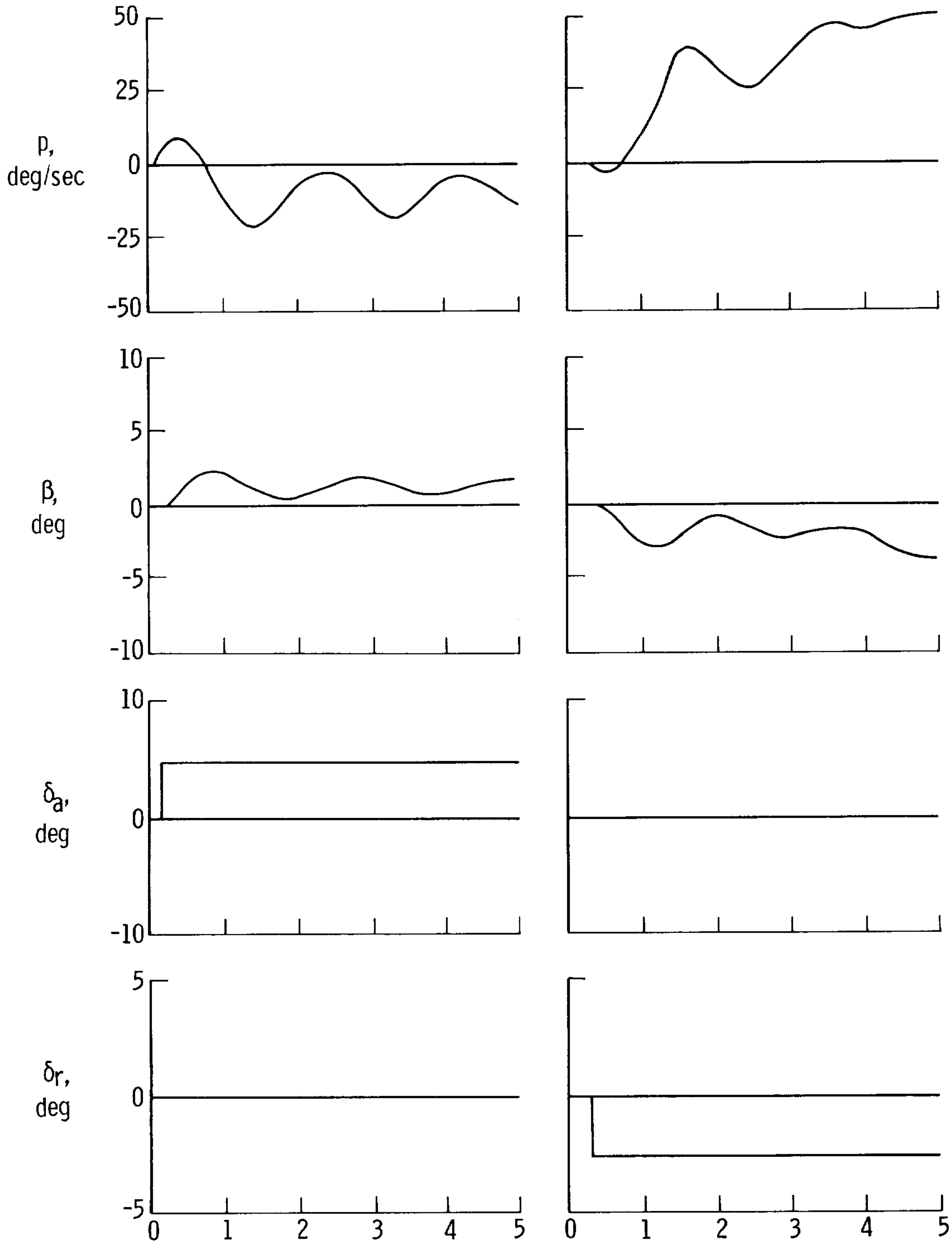

(a) $\delta_a = 5°$.

(b) $\delta_r = -2.5°$.

Figure 19. – M2-F2 simulator-predicted unaugmented response to aileron and rudder inputs. $\alpha = 0°$; $M = 0.4$; $\bar{q} = 150$ lb/ft^2 (7182 N/m^2); $K_p = 0$; $K_r = 0$; $K_I = 0$.

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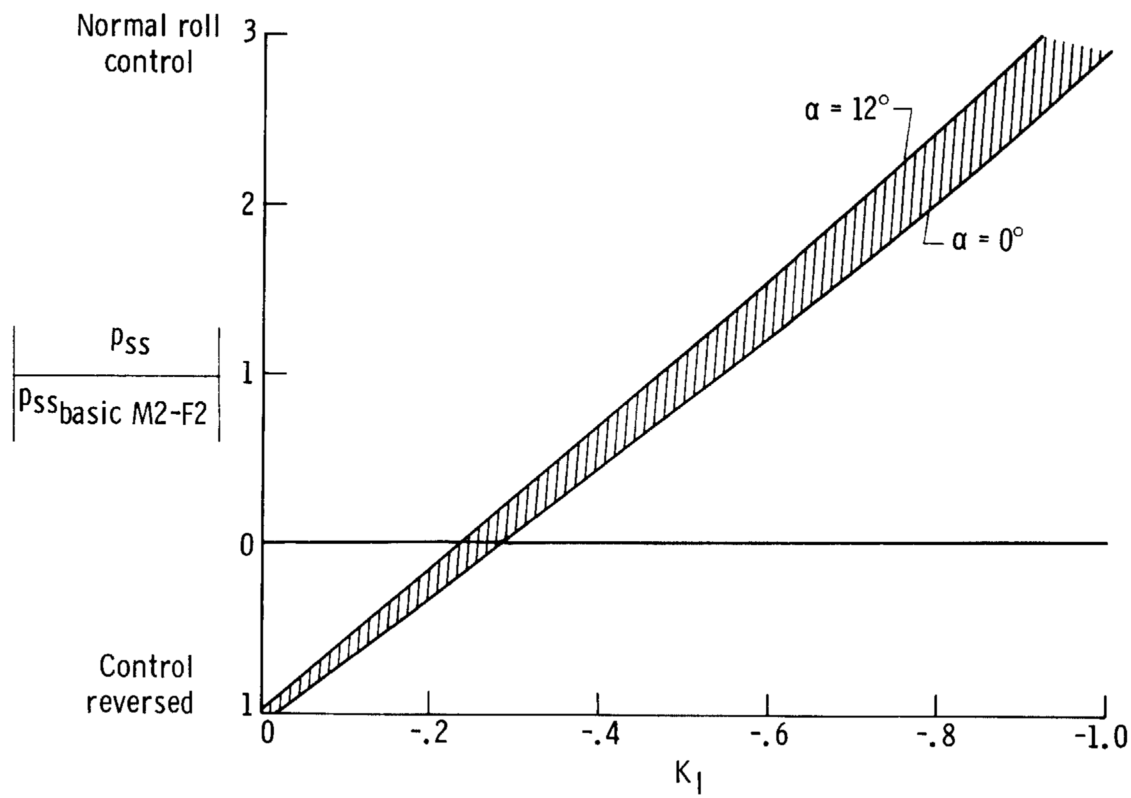

Figure 20.- Calculated M2-F2 steady-state roll-velocity response to aileron ratioed to the M2-F2 basic steady-state roll response as a function of rudder-to-aileron interconnect ratio for an angle-of-attack range of 0° to 12°. M = 0.4.

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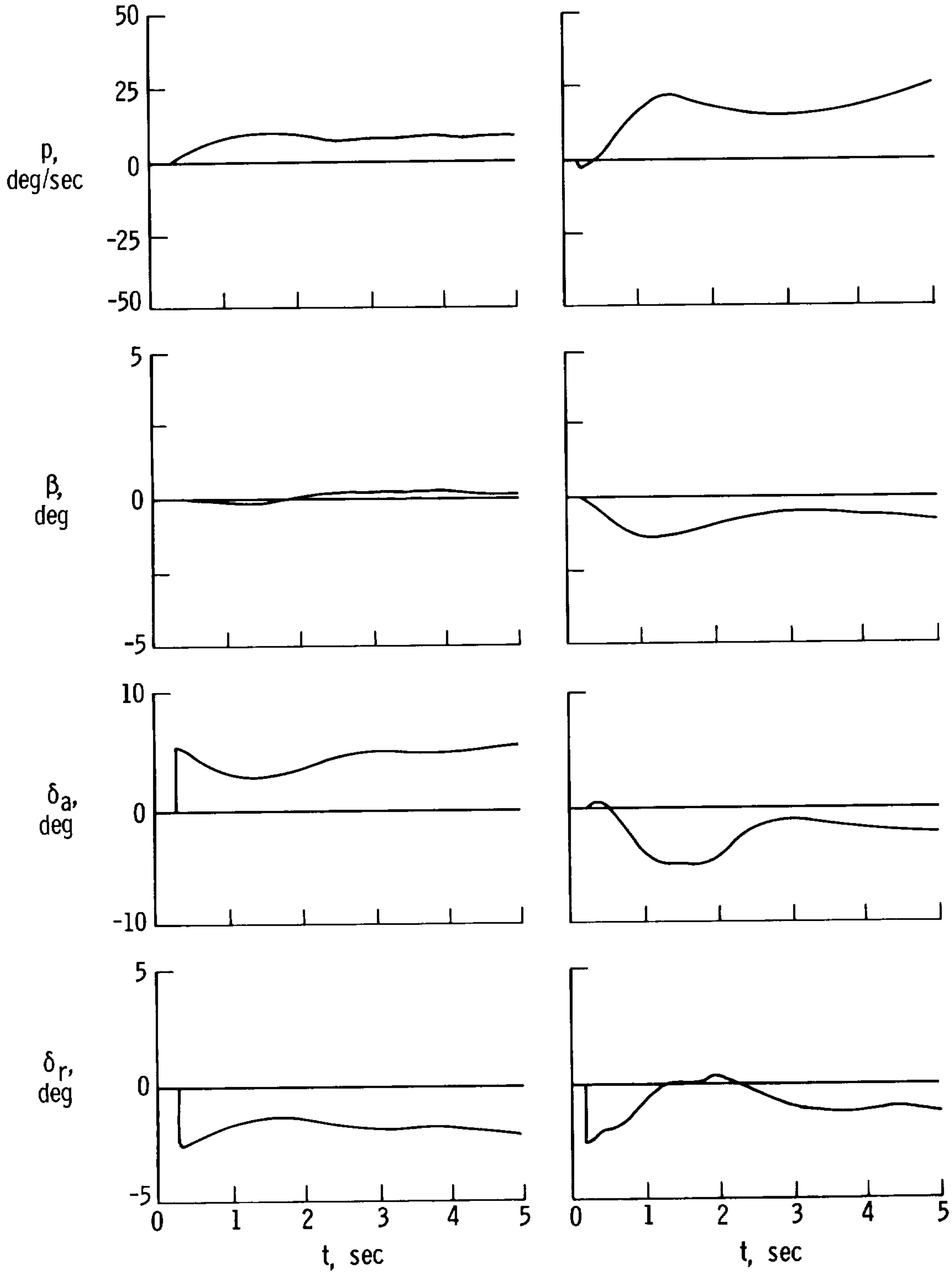

(a) $\delta_a = 5°$.

(b) $\delta_r = -2.5°$.

Figure 21. – M2-F2 simulator-predicted response to aileron and rudder step inputs. $\alpha = 0°$; $M = 0.4$; $\overline{q} = 150$ lb/ft^2 (7182 N/m^2); $K_p = 0.4$; $K_r = 0.6$; $K_I = -0.5$.

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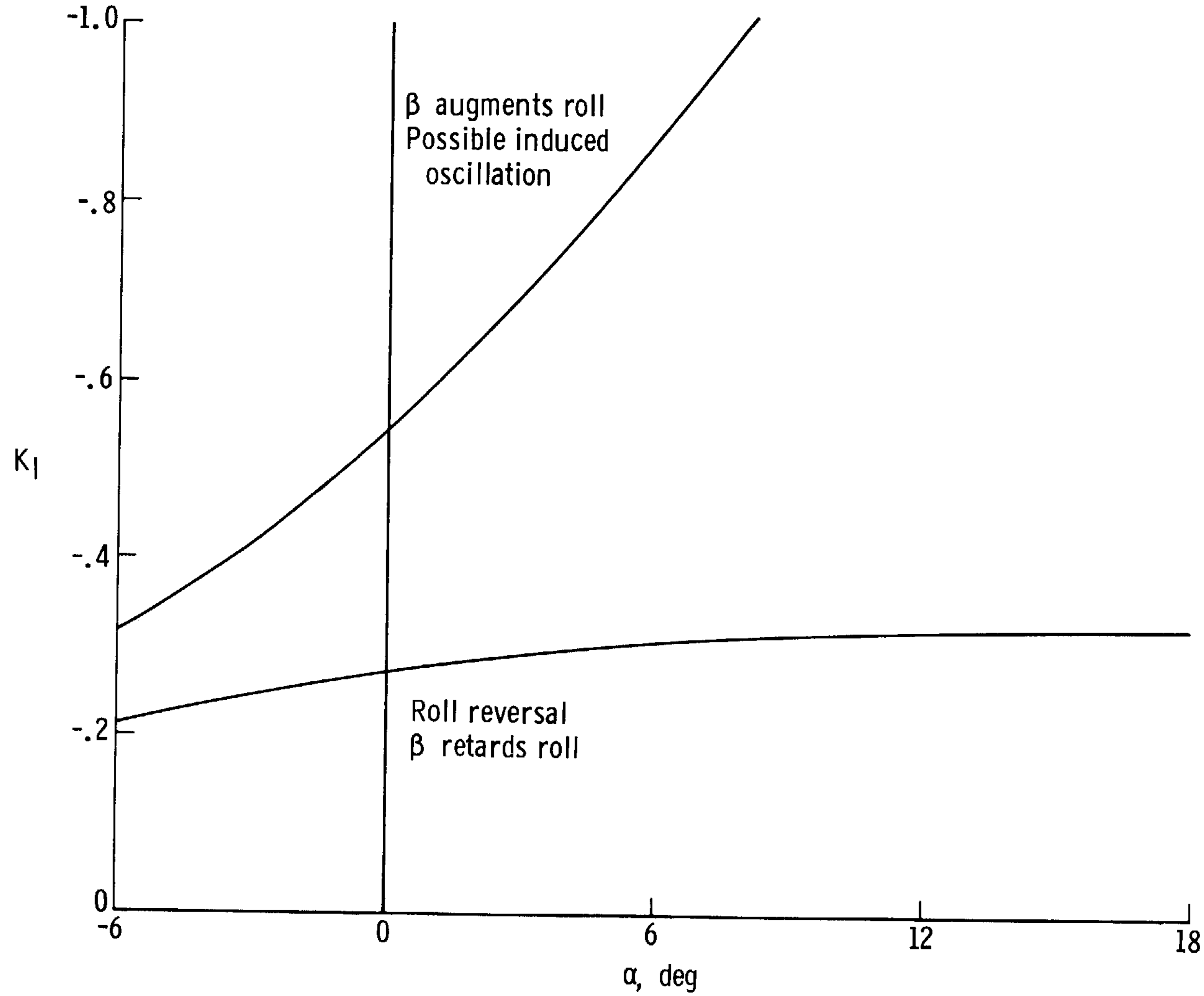

Figure 22.– M2-F2 simulator-predicted regions of basic M2-F2 lateral-control problems as functions of angle of attack and rudder-to-aileron interconnect ratio. M = 0.4.

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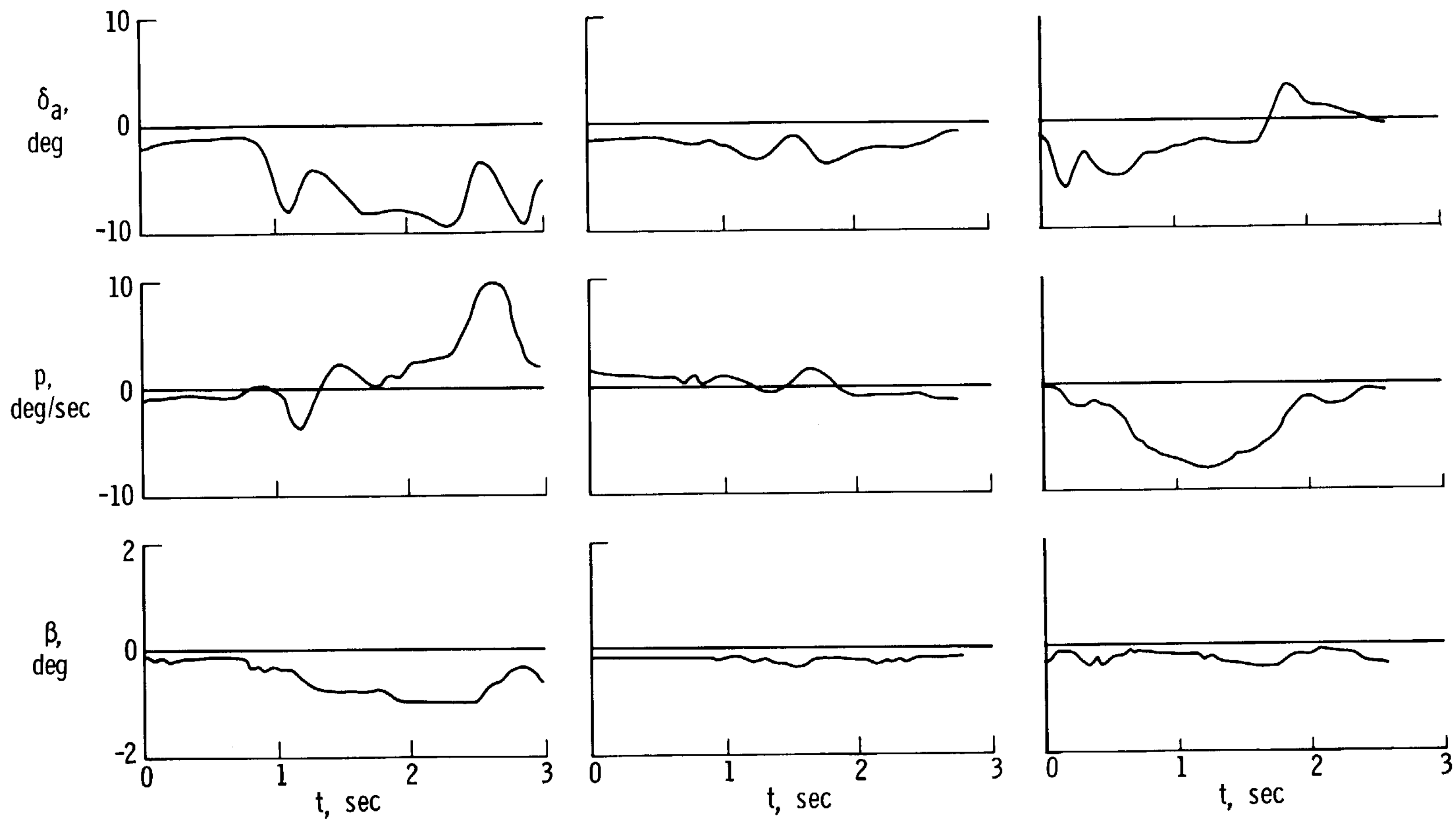

(a) $K_I = -0.20$.

(b) $K_I = -0.53$.

(c) $K_I = -0.79$.

Figure 23. – Time histories of M2-F2 in-flight response to lateral control showing the effect of rudder-to-aileron interconnect. $M = 0.6$; $h = 39,000$ ft (11,887 m); $\alpha = 7°$; $K_q = 0.6$; $K_p = 0.4$; $K_r = 0.6$.

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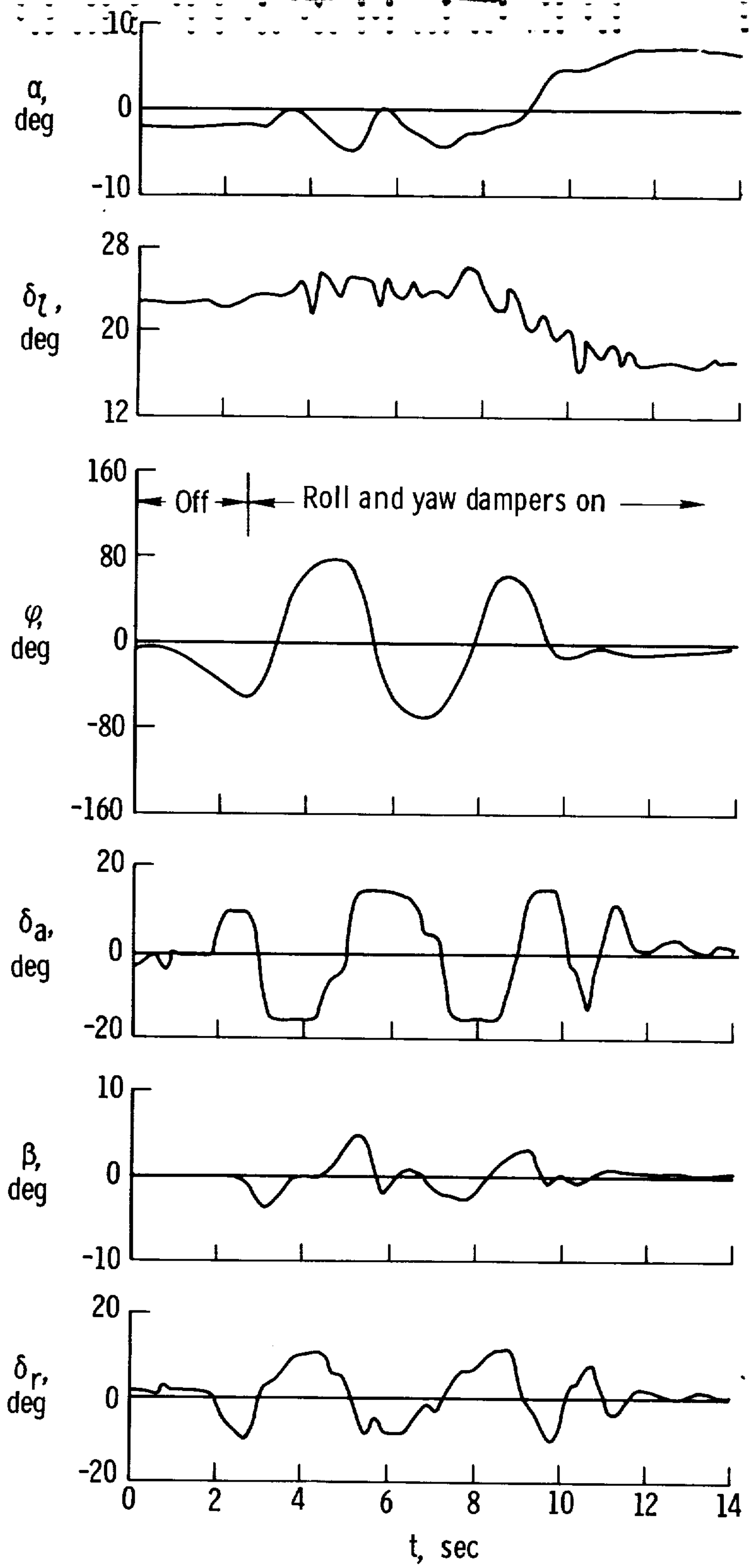

Figure 24. – Time history of an induced lateral-directional oscillation. M = 0.61; h = 23,000 to 19,000 ft (7010 to 5791 m); $K_q = 0.6$; $K_p = 0.4$; $K_r = 0.6$; $K_I = -0.49$.

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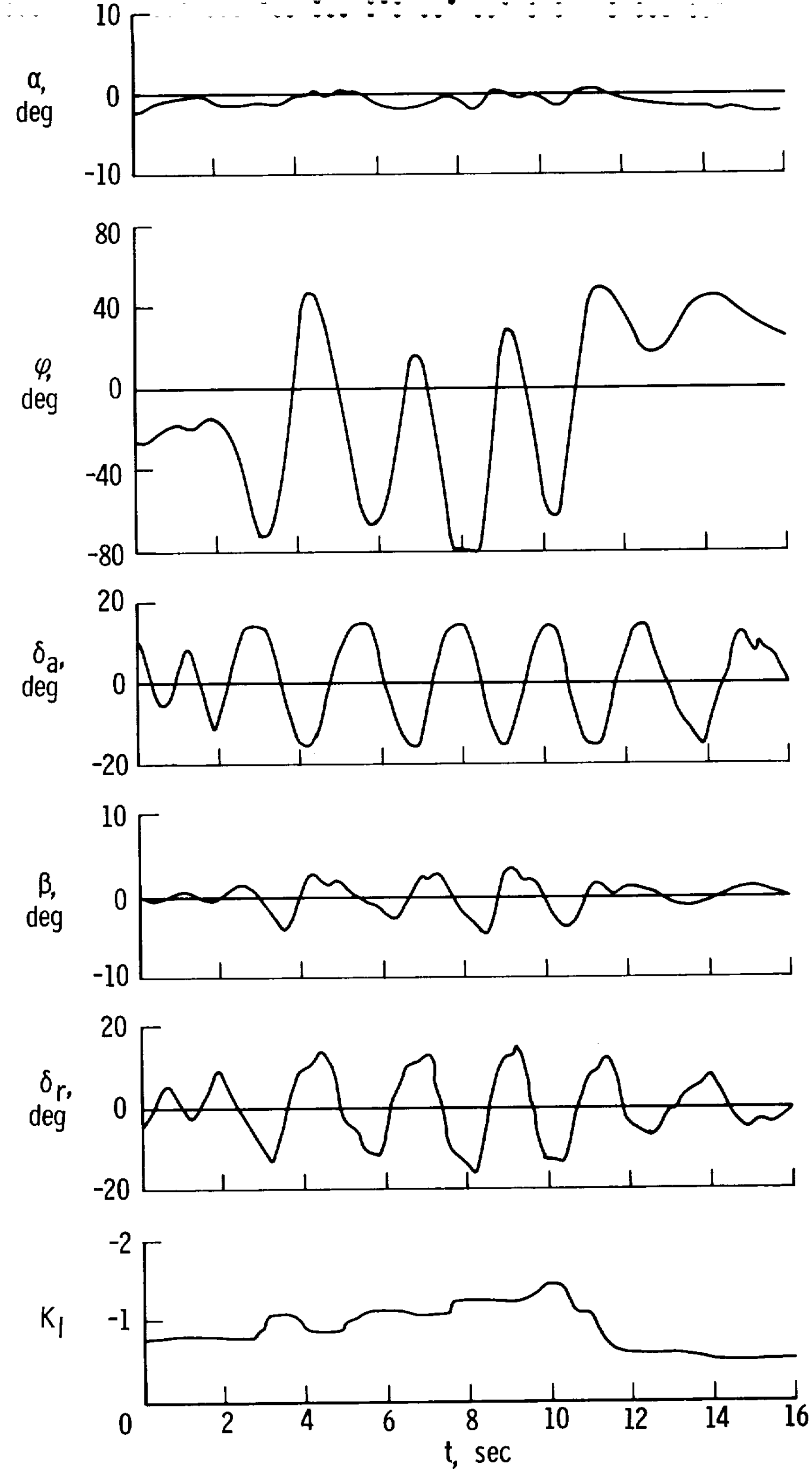

Figure 25. – Time history of an induced lateral-directional oscillation at high rudder-to-aileron interconnect ratio. M = 0.48; h = 9275 to 5500 ft (2827 to 1676 m); $K_q = 0.6$; $K_p = 0.6$; $K_r = 0.6$.

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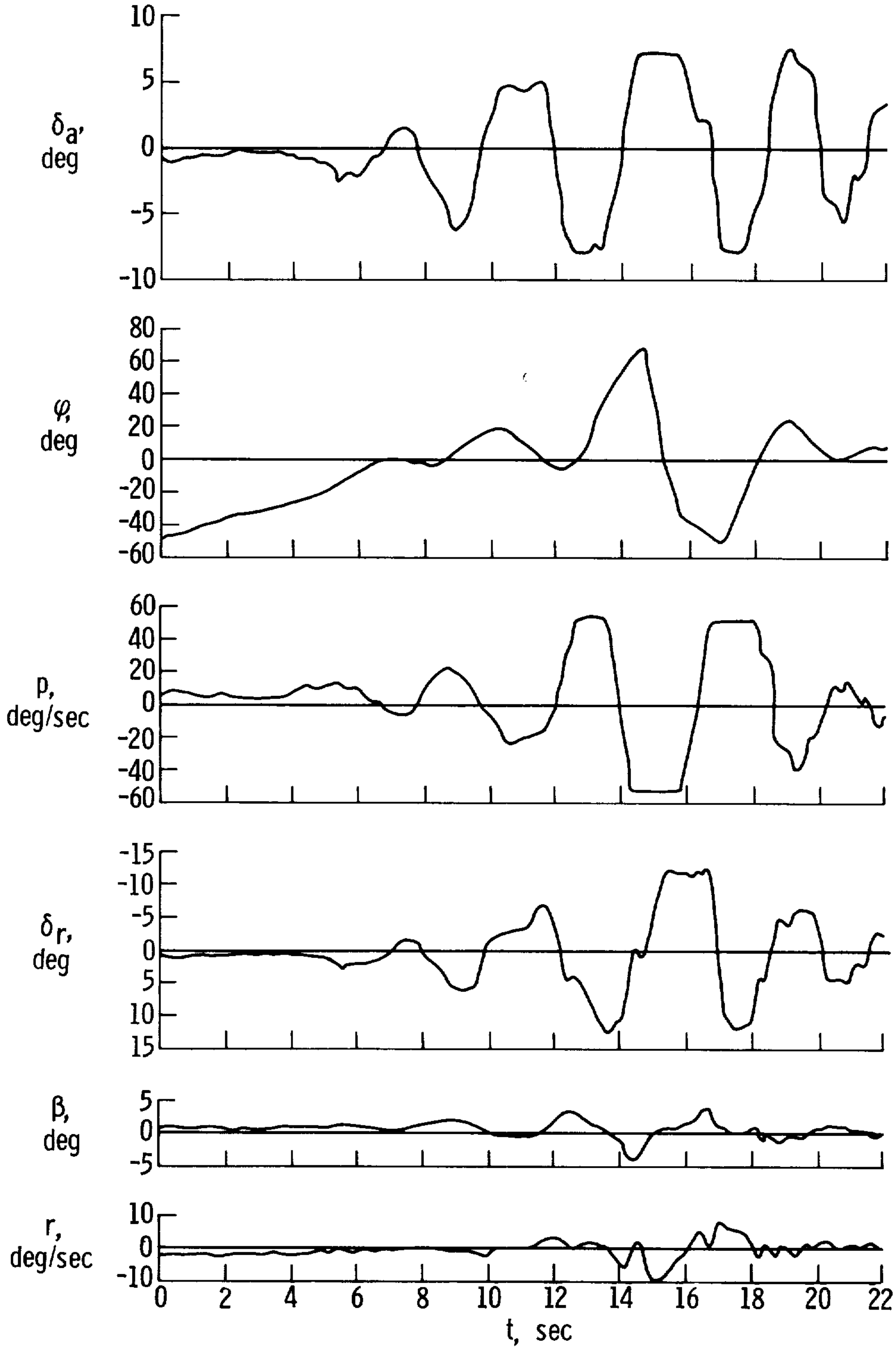

Figure 26. – Time history of an uncontrolled M2-F2 lateral-directional oscillation during final approach to a landing. Initial conditions: M = 0.48; h = 8577 ft (2614 m); α = -2.6°; θ = -39°; $\overline{q}$ = 253 lb/ft^2 (12,114 N/m^2). K_q = 0.6; K_p = 0.2; K_r = 0.4; K_I = -0.45.

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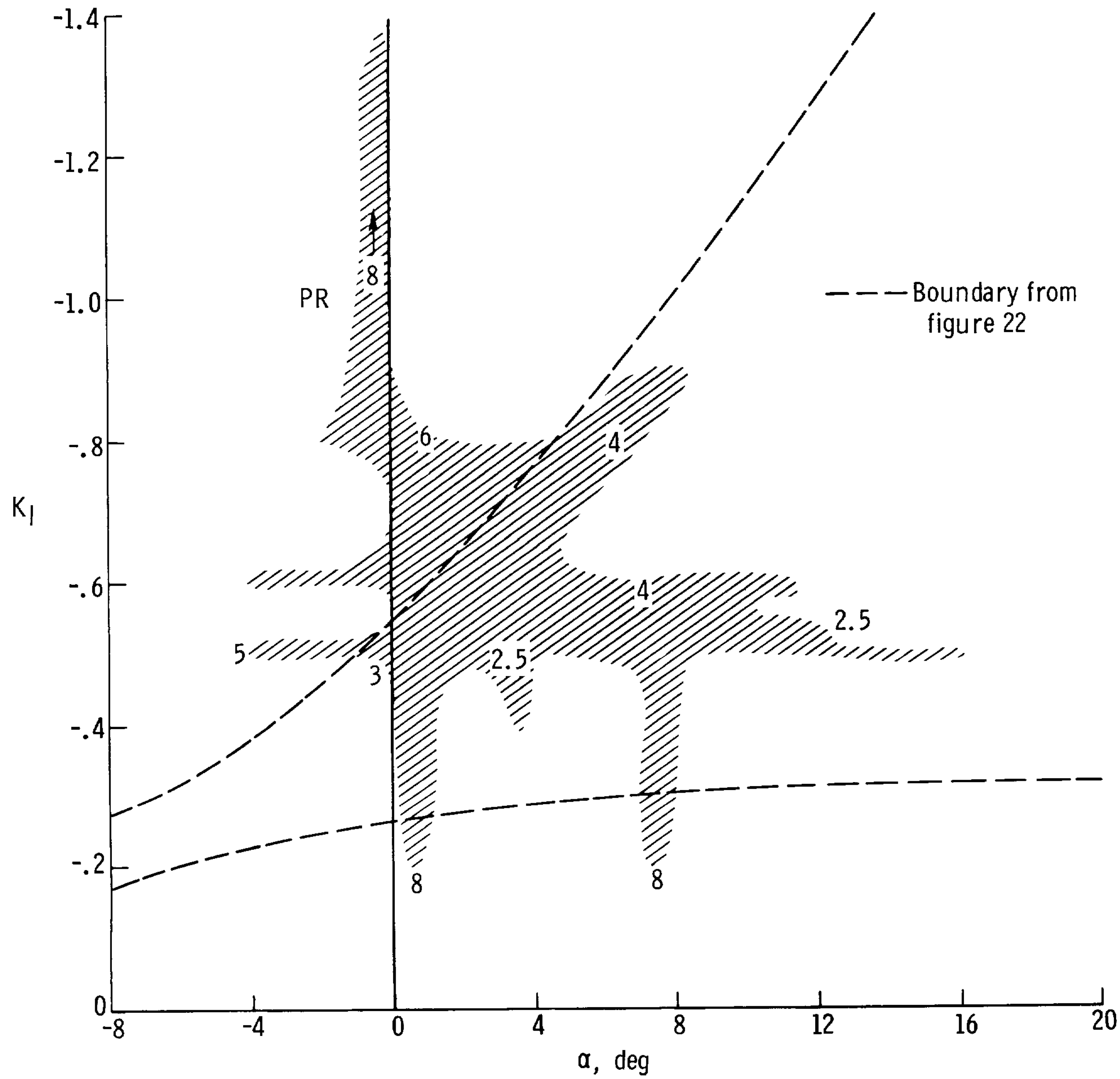

Figure 27. – The rudder-to-aileron-interconnect and angle-of-attack envelope covered during the lateral-controllability investigation, including pilot ratings (PR) of lateral control. $K_p = 0.4$; $K_r = 0.6$.

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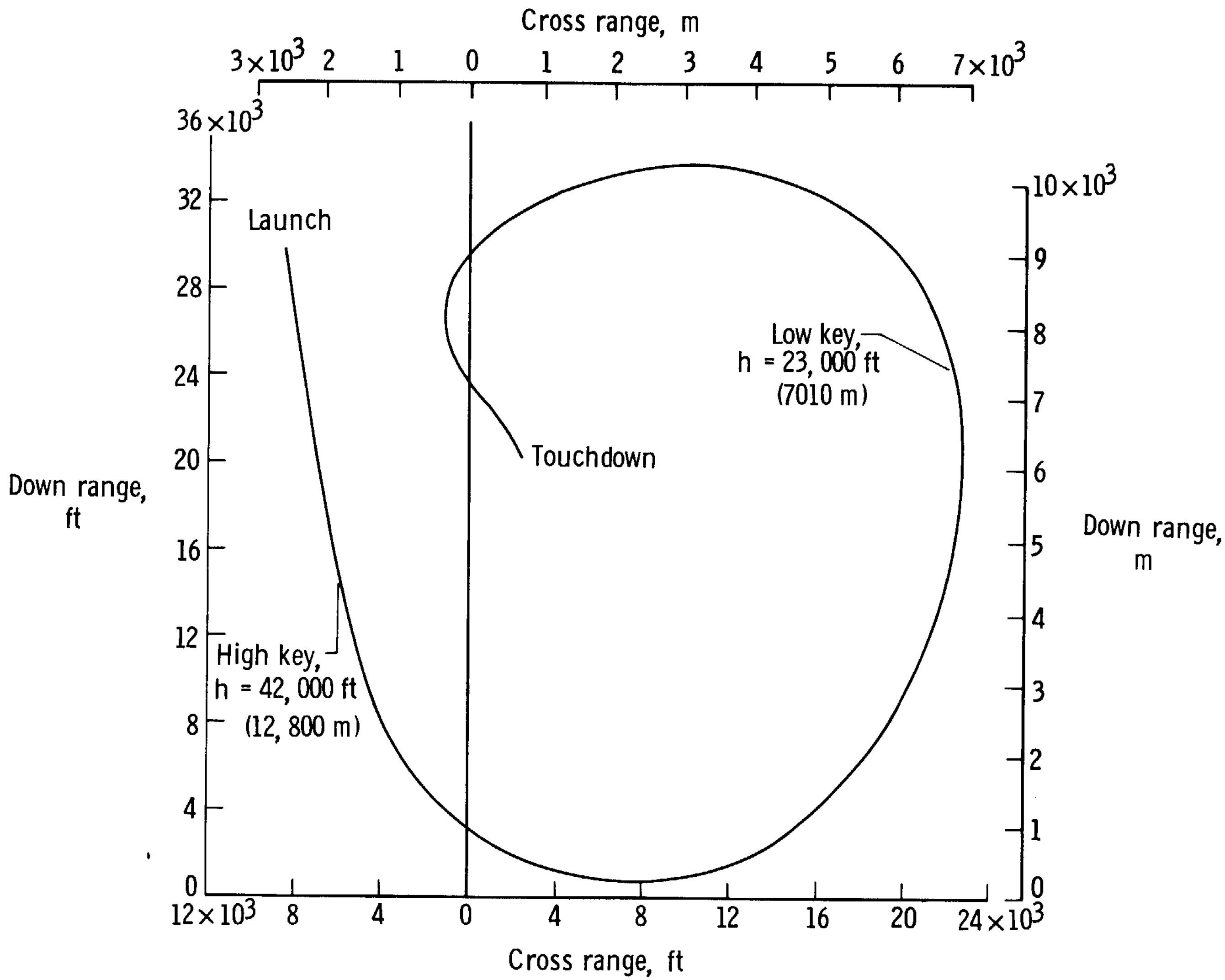

Figure 28. – Plan view of the M2-F2 approach-mission flight.

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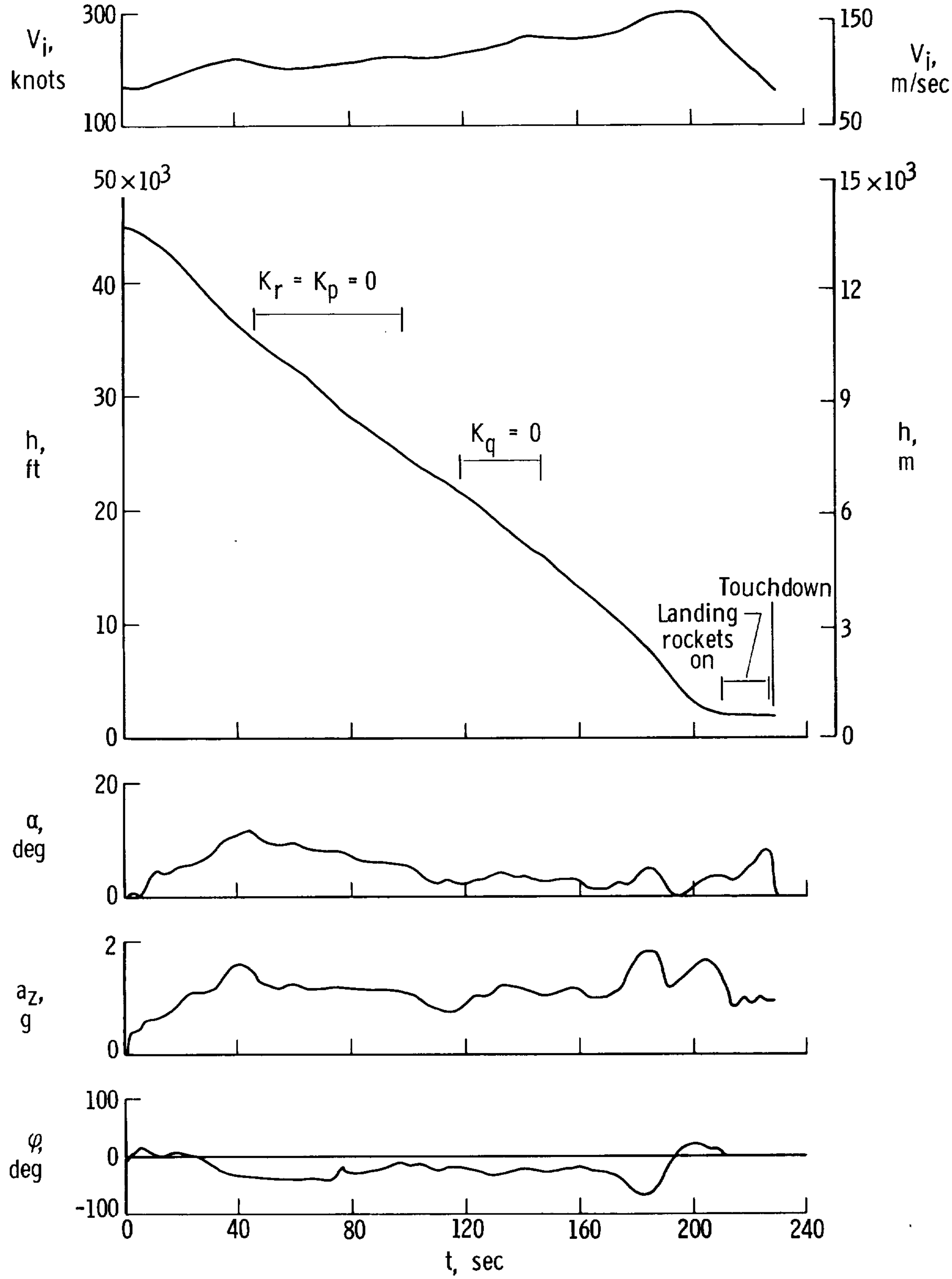

Figure 29. - Time history of the M2-F2 approach-mission flight from B-52 launch to landing. $K_q = 0.6$; $K_p = 0.4$; $K_r = 0.6$; $K_I = -0.5$.

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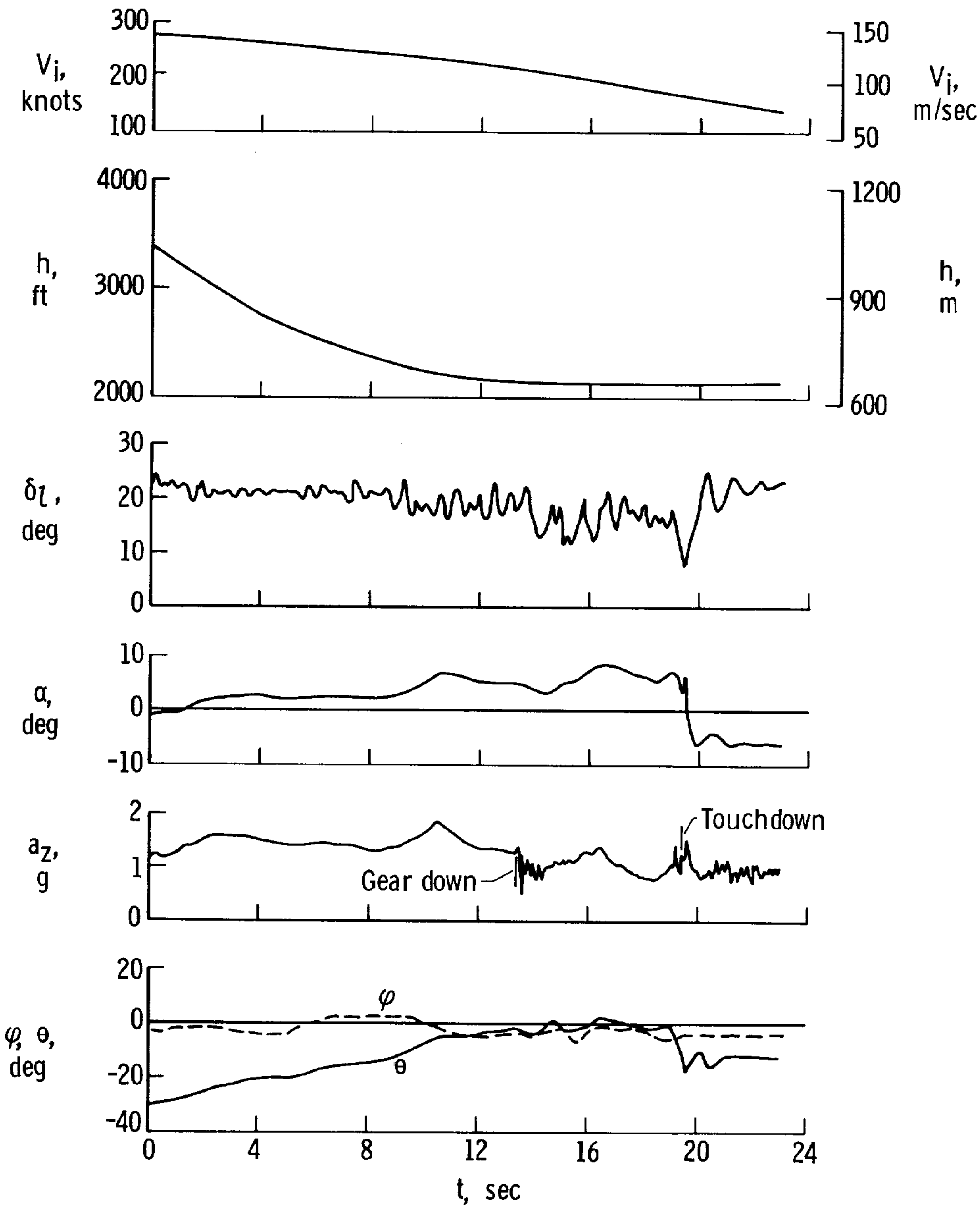

(a) First landing, pilot 1. $\delta_u = -11.8°$; $K_q = 0.6$; $K_p = 0.6$; $K_r = 0.6$; $K_I = -0.5$.

Figure 30 – Time histories of flares and landings with the M2-F2. Center of gravity = 54 percent c; $\delta_{r_o} = 5.0°$.

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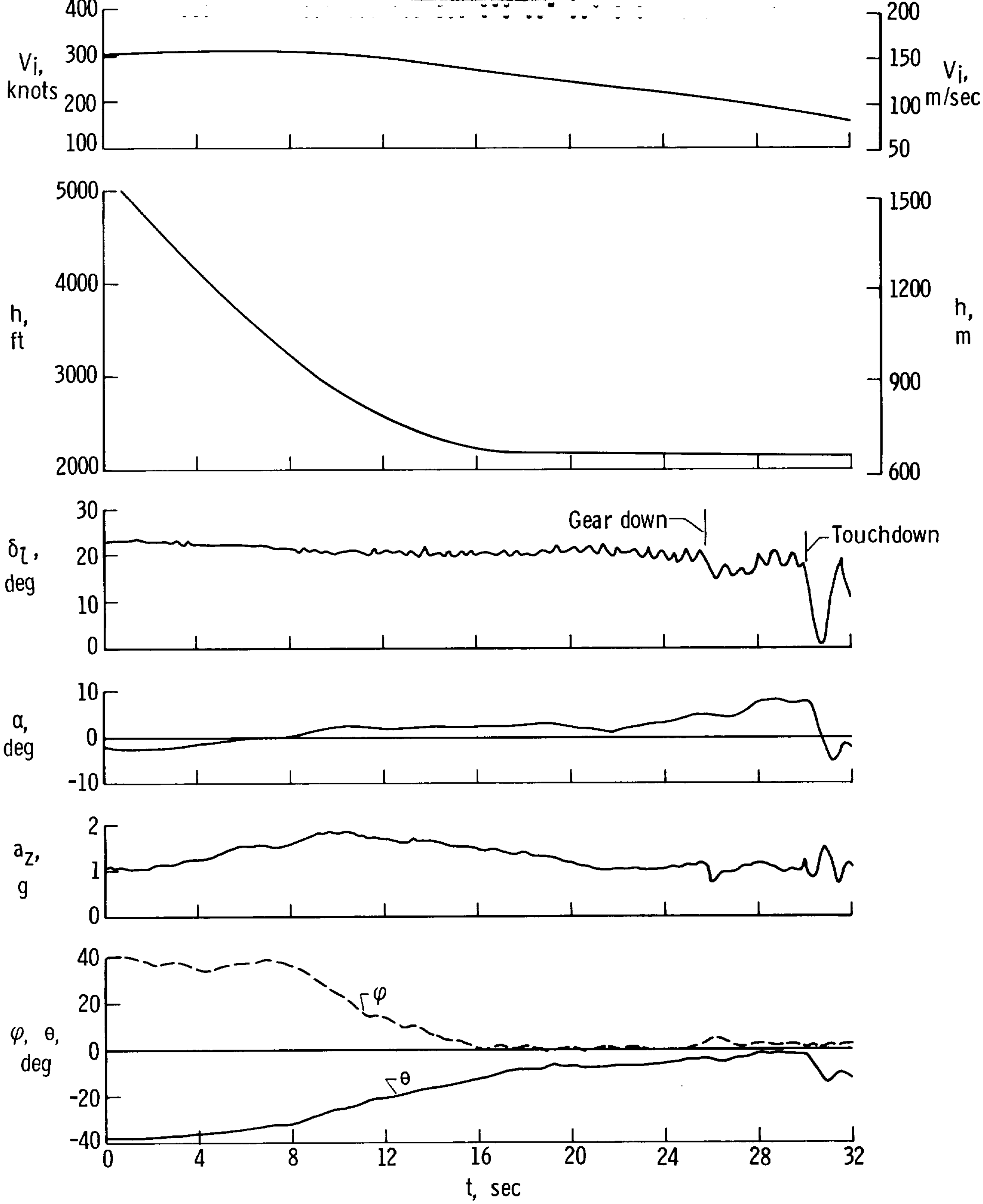

(b) Second landing, pilot 3. $\delta_u = -11.3^\circ$; $K_q = 0.6$; $K_p = 0.4$; $K_r = 0.6$; $K_I = -0.5$.

Figure 30. – Concluded.

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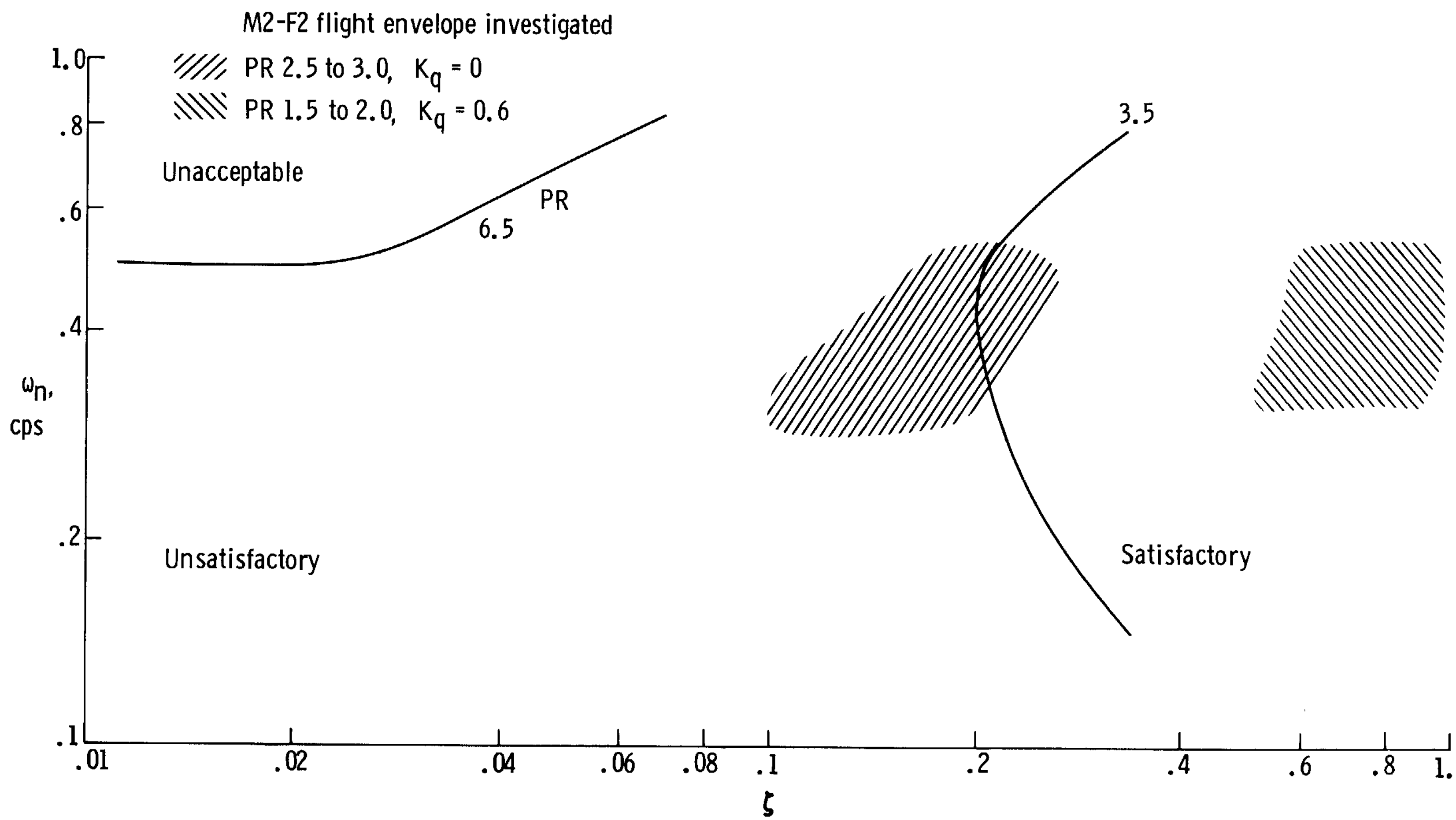

Figure 31. – Comparison of M2-F2 longitudinal handling with the proposed criterion of reference 11.

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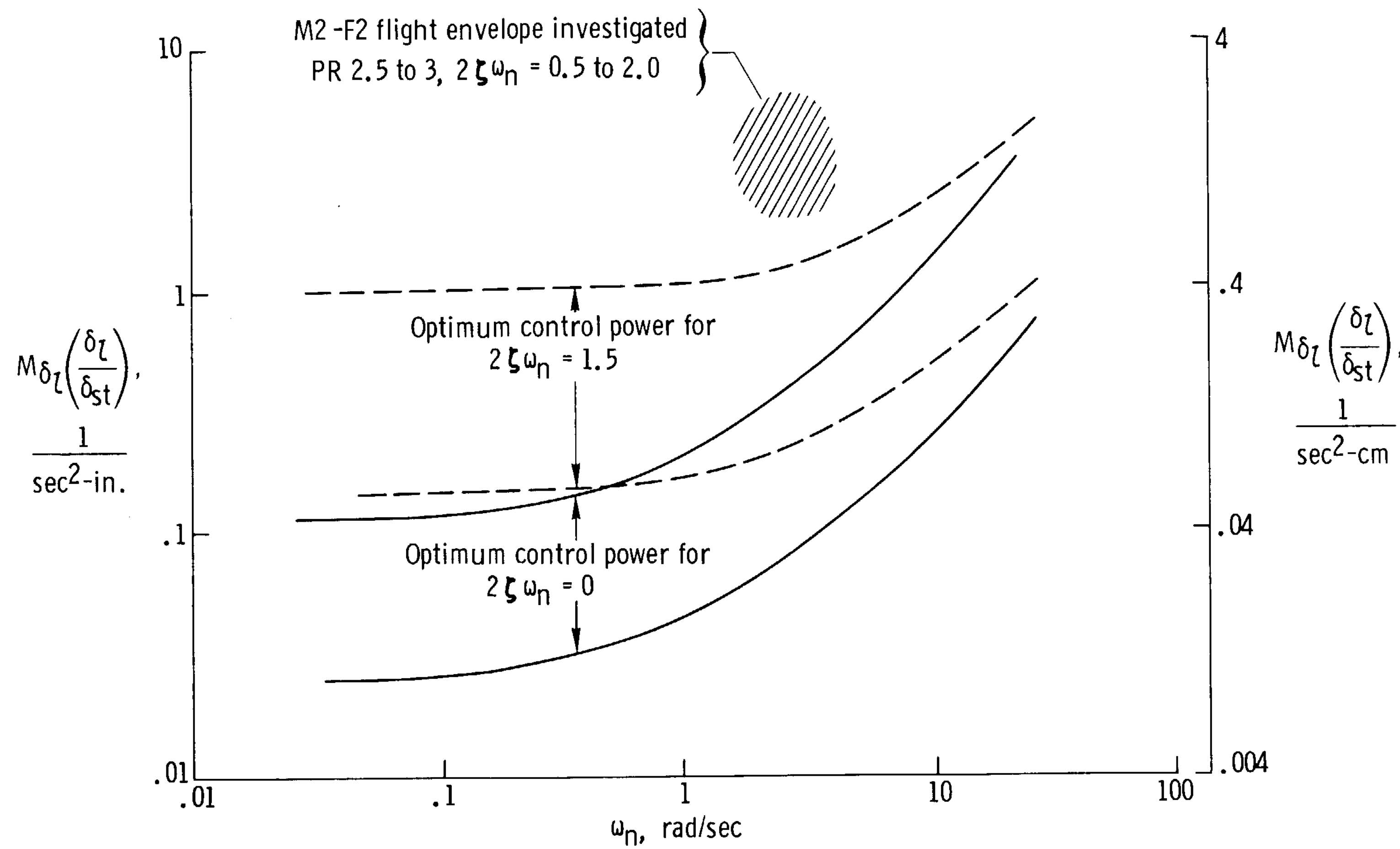

Figure 32. – Comparison of the unaugmented M2-F2 longitudinal-control effectiveness with the proposed criterion of reference 11.

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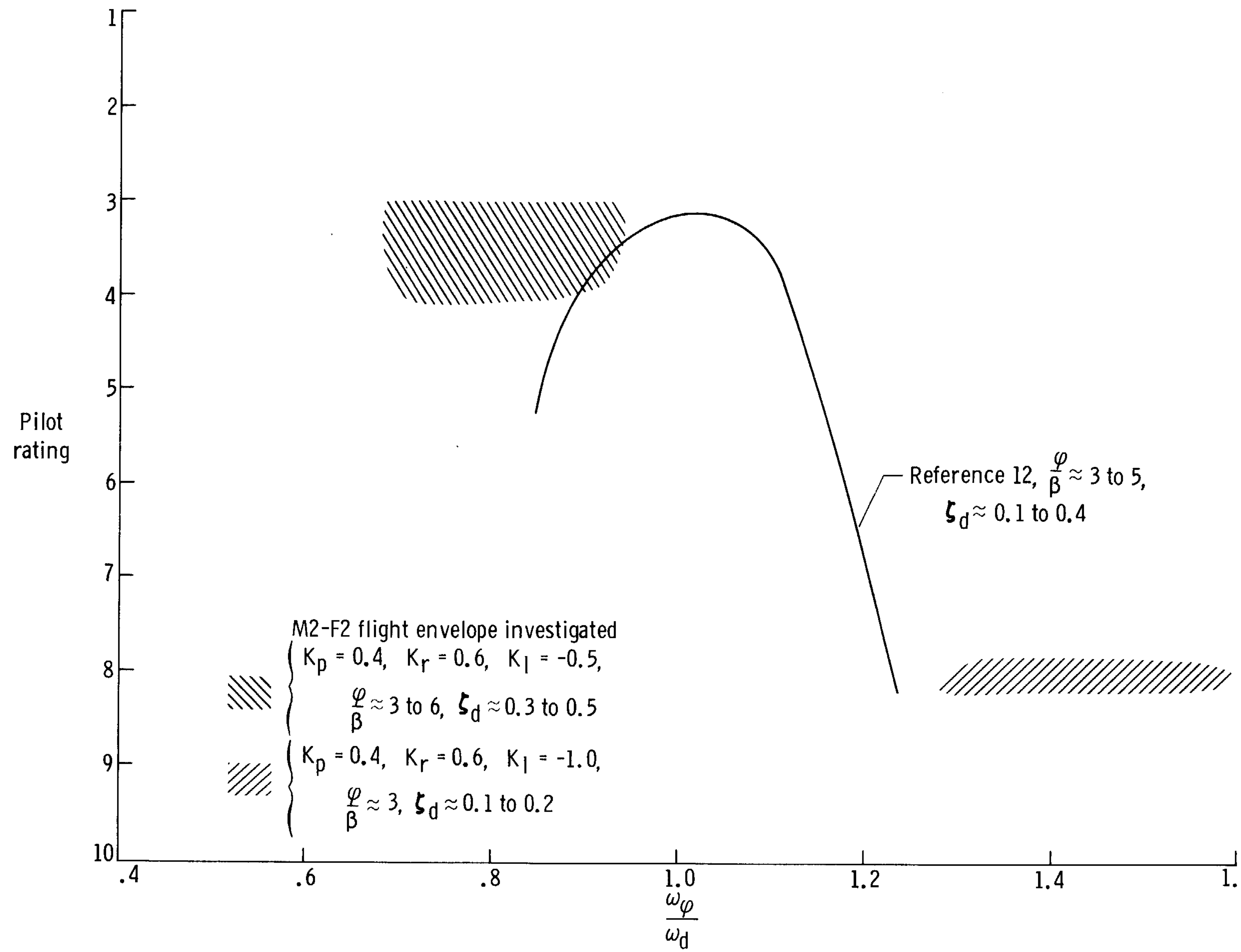

Figure 33. – Comparison of the M2-F2 in-flight lateral-directional handling qualities and the predictions of reference 12.

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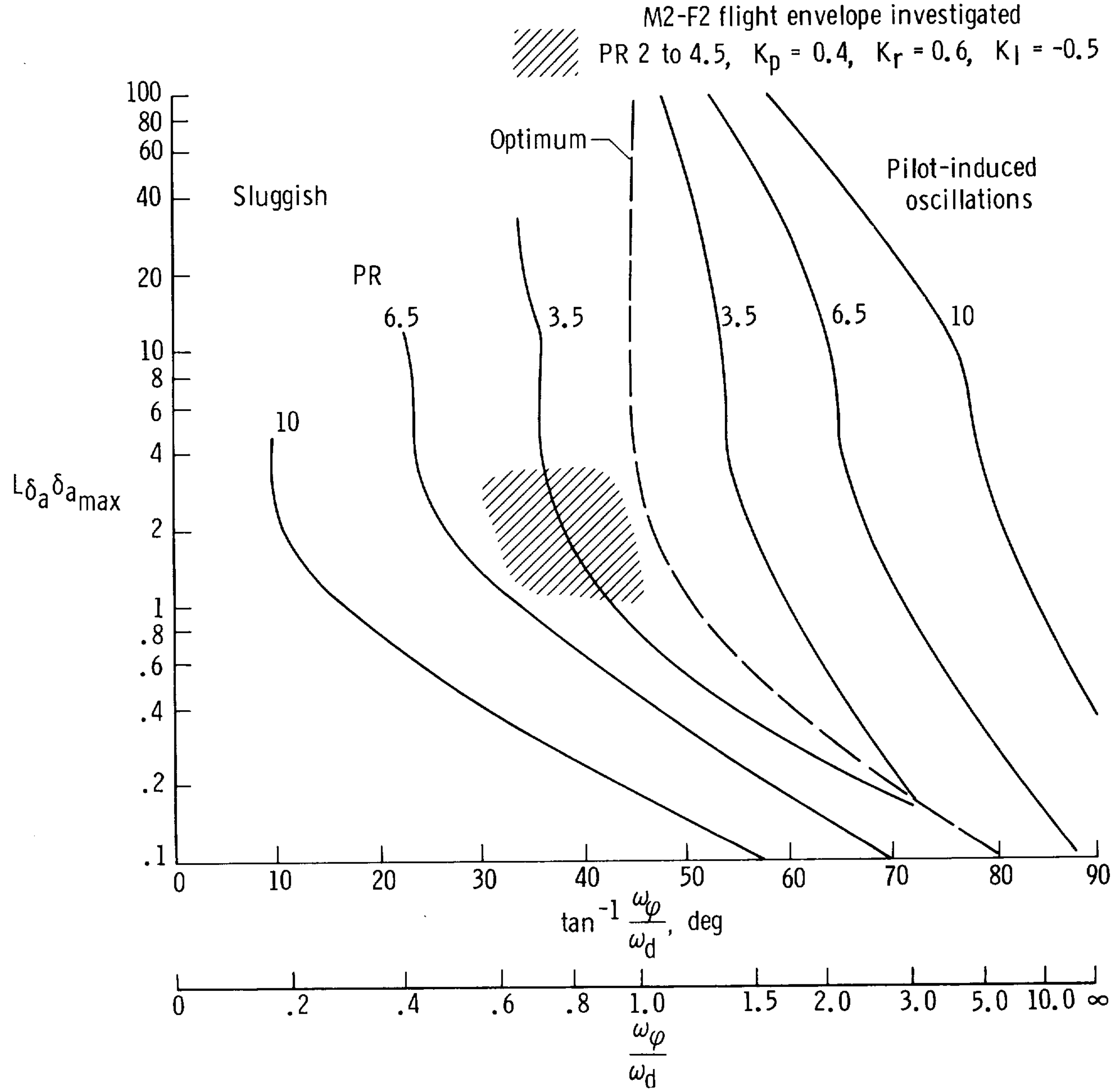

Figure 34.– Comparison of the M2-F2 with dampers and interconnect operative with the results of reference 13. $\omega_\varphi + \omega_d > 3.0$; $|L_\beta| > 10$; $2\zeta_d\omega_d = 1.0$; $\frac{1}{\tau_R} = 4.0$.

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